NUCLEONICS

July 1953

Distribution of uranium ore deposits is studied in laboratory by simulating Colorado Plateau, with "rain" falling on "mountains" in rear, right. Wheel is used to study effect of water flowing in stream on size and sphericity of heavy ore particles (see p. 59)

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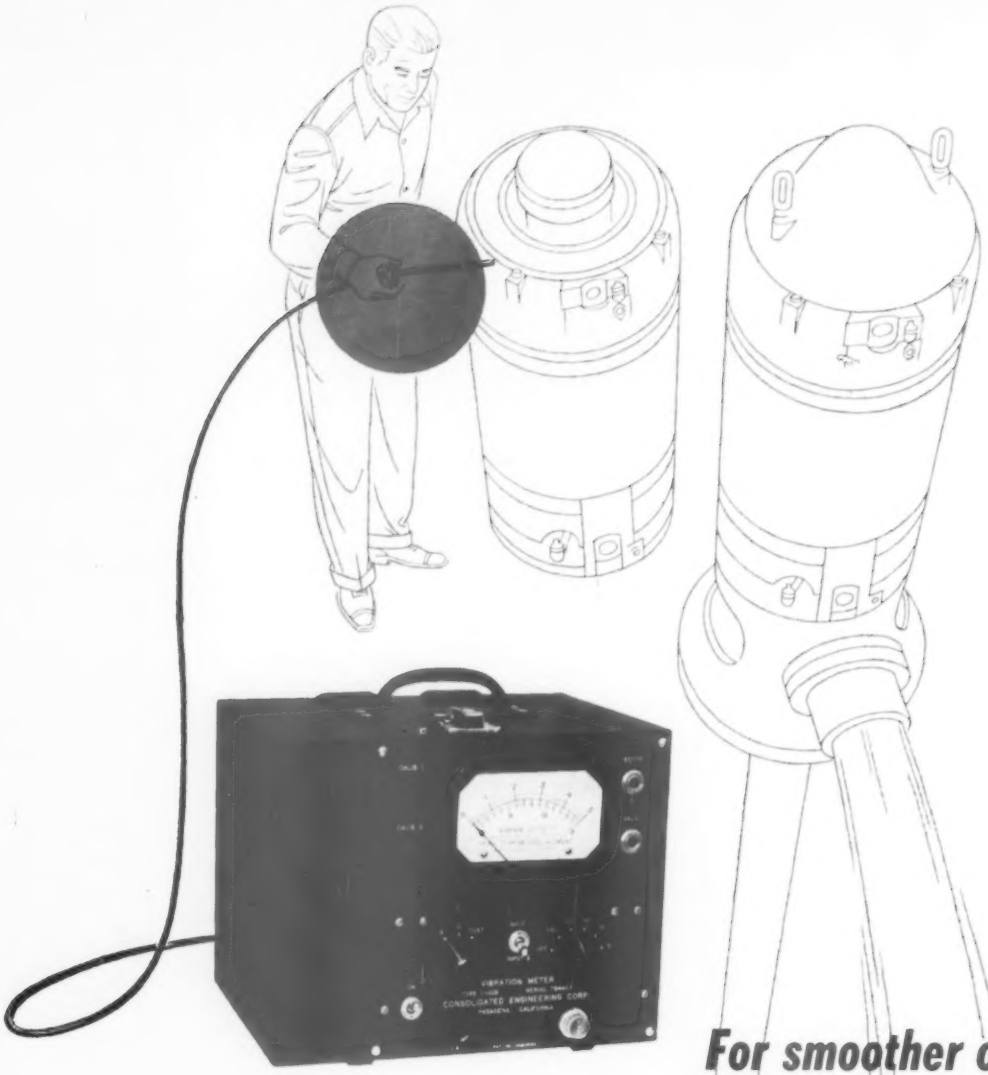

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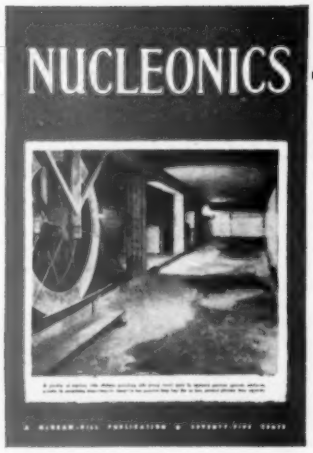

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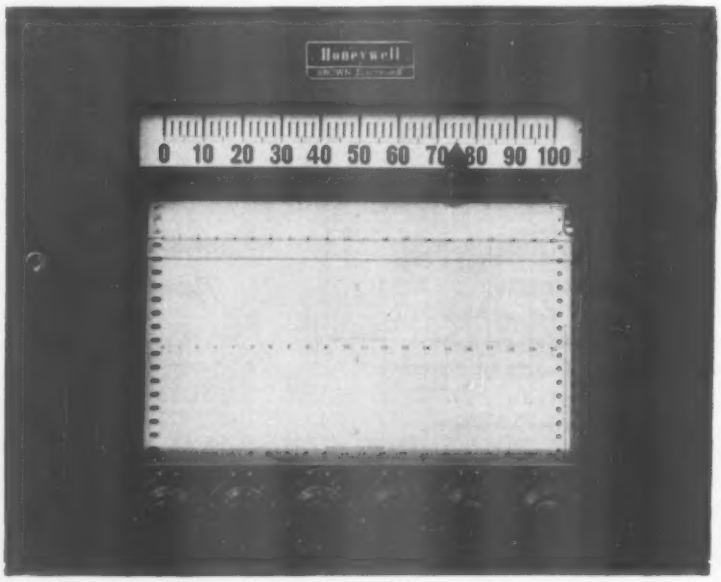

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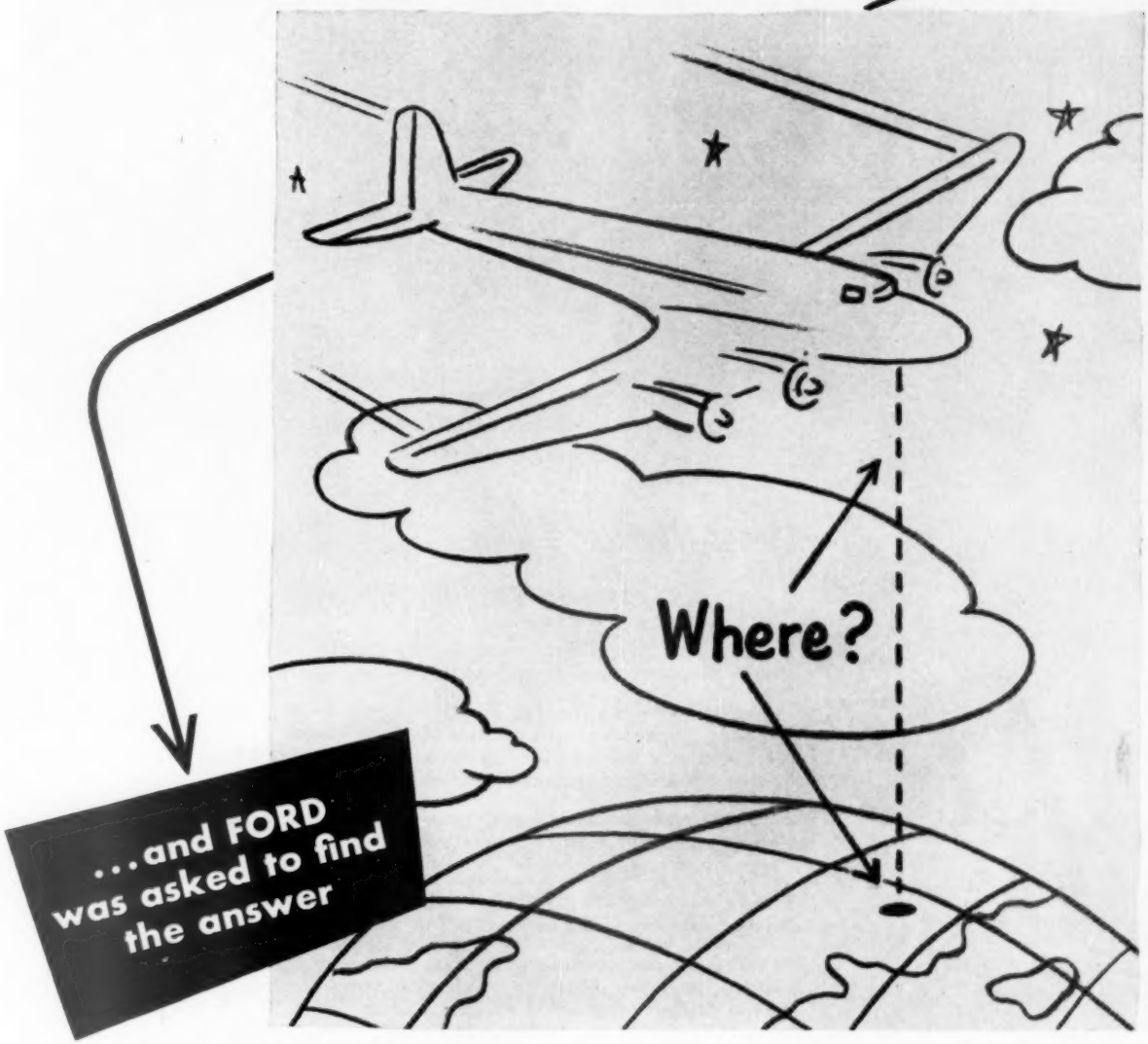

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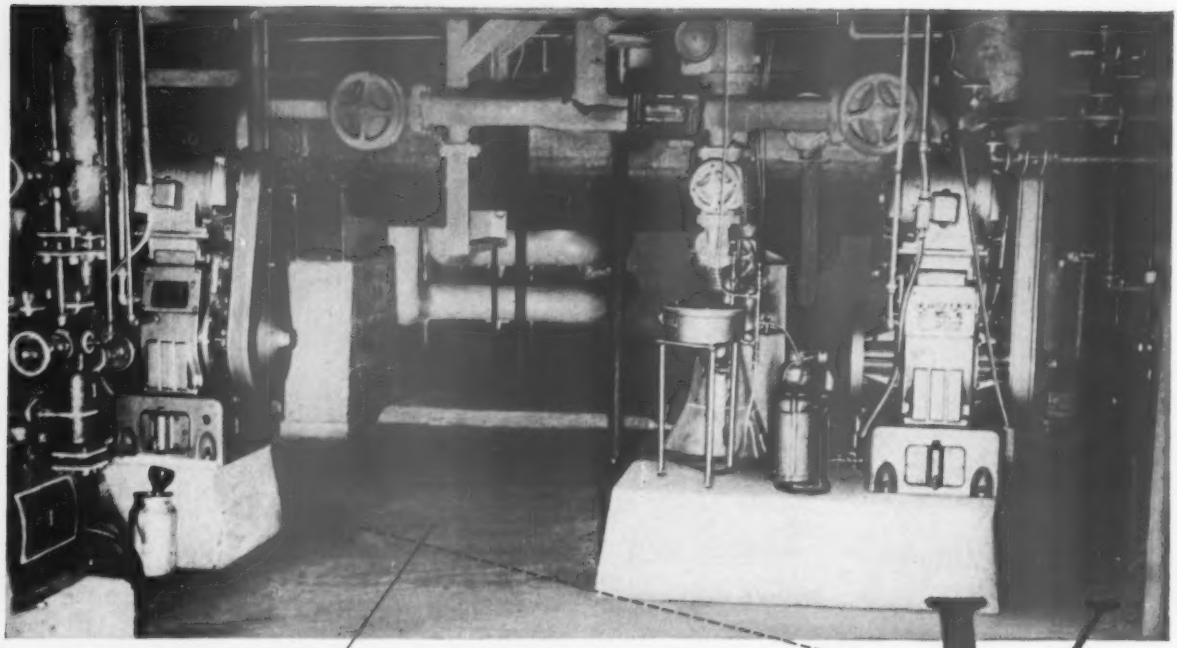

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NUCLEONICS JULY, 1953

Jerome D. Luntz, *Editor*

An Important Milestone

BREEDING WAS VERIFIED experimentally for the first time last month. This is a scientific accomplishment whose effects will one day be felt around the world. It doesn't by any means imply that economic nuclear power is just around the corner. Rather it is material evidence of the great potential for technical advance in this country that will bring us closer to this goal.

The formulation of the principle of breeding (producing more fissionable material than is consumed in a reactor) was the natural outcome of the discovery that more neutrons are produced in the fission process than are needed to sustain a chain reaction. The trick then was to use these excess neutrons as efficiently as possible to convert fertile materials, such as U-238 and Th-232, into fissionable isotopes.

The reactor neutron economy is a very strict one with the margin of neutrons available for breeding quite small. Because the expectations for breeding gain in thermal reactors were more modest than in fast reactors, Argonne National Laboratory went to the use of fast neutrons in its breeder reactor (EBR). No moderator is necessary and demands on the materials are less stringent.

It was in this reactor that the breeding principle was confirmed. It is an experimental reactor, a scientific tool, one designed primarily to make measurements.

Although it produced token amounts of electricity, EBR is not a power reactor. It was built solely to test the theory. In fact, according to W. H. Zinn, director of Argonne, "more such experimental devices may be necessary before we are on sure ground as to the fundamental feasibility of the process."

Many headaches lie ahead in translating the breeding principle into the framework of a large-scale power reactor. The Dow-Detroit team of more than 200 men is trying to do just this.

The differences between breeding in EBR and breeding in a large reactor are considerable—differences in physical configuration, power density, operating temperatures, etc. These are engineering problems that must be resolved, partly on paper, more importantly in actual plants.

High on the list of problems is the development of a low-cost chemical processing system. There is the need for frequent, efficient recovery of fissionable material. In fact the efficiency of the chemical system can be the determining factor in whether or not you are breeding in a practical sense. Unless this problem can be resolved successfully, low-cost fuel would be a figment of the imagination and the breeder would have difficulty competing with the simple regenerative converter.

THE SUCCESS OF EBR will give a tremendous psychological boost to nuclear engineers working on power breeders, the same kind of boost that any engineer gets from the knowledge that his goal is possible of achievement.

But of even greater significance is the meaning that breeding holds for world supplies of fissionable materials. Total economically recoverable conventional energy resources are said to be 80×10^{18} BTU. Without breeding, the energy reserve in U-235 is 12×10^{18} BTU. But with breeding, complete use of the world's reserves of 25 million tons of uranium and 1 million tons of thorium would yield almost $1{,}800 \times 10^{18}$ BTU. This would provide the basis for a very substantial nuclear power economy.

But there is no need to wait for power breeders for the development of a nuclear power industry. This is the long-term goal. Meanwhile, we have an energy reserve in U-235 that is many times that in the world's oil reserves. Yet, as pointed out in the May NUCLEONICS by Karl Cohen, the industries based on the use of oil are very substantial.

Flux Depression and Self-Protection in the Production of Radiocobalt

For reactor production of large, high-specific-activity sources, calculations to correct for self-protection and flux depression are difficult. This article describes an experimental evaluation of the effects for cobalt sources

By J. S. LEVIN and D. J. HUGHES
Brookhaven National Laboratory
Upton, New York

FOR MANY applications, it is desirable to use radioisotopes that have both high total activity and high specific activity. For those few activities produced by (n,p) and (n,α) reactions, such as P^{32} and C^{14}, the pure (carrier-free) radioisotope can be produced by chemical separation from the target.

The great majority of radioisotopes are produced by neutron capture, however, and for these the attainable activity is given directly by the maximum available neutron flux, and the total activity is given by the amount of material that can be irradiated in that flux.

For a material of high capture cross section, of which cobalt, with 34.8 barns (*1*),* is an outstanding example, the effort to produce large, high-specific-activity sources may cause a serious decrease in activity, however. A thick sample will absorb enough neutrons so that the nuclei in the center of the foil will be in a lower flux than those at the surface; this *self-protection* effect can be calculated reasonably well for cobalt, for which the absorption is larger than scattering. An accurate calculation, however, is difficult because the angular distribution of the incident neutrons, which is not simple near a strong absorber, must be taken into account.

In addition to the self-protection effect, the effective flux will be reduced further for a strong absorber when, as is usually true, it is irradiated in a diffusing medium. This *flux depression* results from the net flow of neutrons into the absorber, a flow which necessarily implies a flux gradient near the absorber.

The depressed flux is calculated from diffusion theory by inclusion of a negative source, of strength given by the number of neutrons absorbed by the sample per unit time. The calculation can be carried out by elementary diffusion theory only if the sample is a thin spherical shell.

The plane-foil case has been evaluated by Bothe (*2*) and checked experimentally by Klema and Ritchie (*3*). The results for these geometrically simple cases show that the flux depression can easily be larger than self-protection; this emphasizes the necessity of experimental determination for actual samples, for which calculations are impractical.

Because of the difficulty of calculation and the evident lack of agreement between calculated and observed activity of radiocobalt sources (*4*), it was decided to measure the self-protection and flux depression for two actual cobalt sources. The first to be investigated was a solid cylinder, 3 cm long and 0.75 cm in diameter, which was to be irradiated inside beryllium. This cylinder is to be used in a teletherapy unit at the University of Chicago.

The second sample was one of the cobalt cylinders routinely used at Brookhaven for production of "kilocurie" sources. It was a cylindrical cobalt shell 12¼ in. long, with an outside diameter of 1.045 in. and a 0.125-in. wall thickness, clad inside and out with 0.045 in. of 2S aluminum.

The neutron flux distribution in and near the cobalt samples was measured by irradiation of thin (so as to produce no flux distortion) copper foils. Copper was chosen because it has a convenient half-life (4.3 min) and also has a ratio of resonance activation to thermal cross section similar to that of cobalt (*5*). This latter property ensures that no relative error will be introduced by resonance activation of the cobalt or copper.

The cylinders were placed at appropriate positions in the lattice or thermal column of the Brookhaven pile for

* About 40% of the captures lead to the 10.7-min isomeric state of Co^{60}, but 99.7% of the Co^{60} isomer decays into the 5.3-yr Co^{60} ground state.

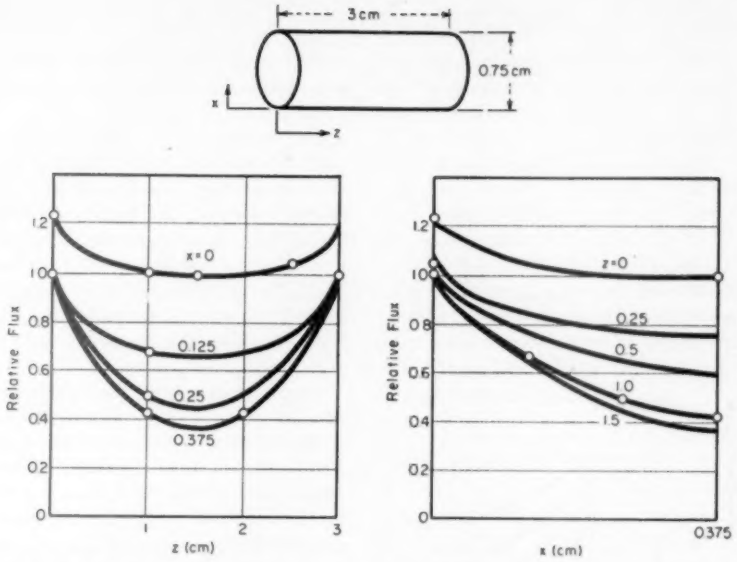

FIG. 1. Neutron flux distribution in small Co cylinder. Flux taken as unity at center of one end of cylinder

irradiation of the copper foils, and the foils were counted after irradiation on end-window G-M counters.

Small Source

In the study of the small solid cylinder, a copy of the source was machined in the form of three pellets, each 0.75 cm in diameter and 1.00 cm long. Circular depressions, 0.050 in. in diameter and 0.005 in. deep, were machined in various places on the flat faces of the pellets. These depressions were used to hold the copper foils used to make the flux measurements. Foils placed on the exterior curved surfaces were held in place with Scotch tape.

The copper foils were 1 mm^2 in area and weighed between 410 and 430 μg; corrections for variation in weight were made wherever necessary. Chemical purity of the foils was not important because of the method used in evaluating the data.

The irradiation of the cobalt cylinder containing the copper foils was carried out in a Lucite box, containing blocks of beryllium arranged to form a cube 6 in. on an edge. To carry out an irradiation, several copper foils were placed in depressions in the pieces of cobalt or else taped on their surfaces, the pieces of cobalt taped together to form a cylinder the size of the cobalt source, and this assembly placed in a cavity at the center of the beryllium cube.

The Lucite box was then placed on the bottom of a $12 \times 12 \times 12$-in. cavity in the thermal column on the top of the Brookhaven reactor. This cavity has at least 2 ft of graphite on all sides, and, therefore, the flux in this region is fairly isotropic. The thermal flux is of the order of 6×10^8 n/cm^2/sec.

The box was left in the thermal column for 6 min, then removed and the foils counted. Another foil, which had been located on the outside of the Lucite box, far from the cobalt, was counted continuously on one counter to obtain a decay curve. The counting rates were of the order of 1,000 to 3,000 cpm about 3 min after the end of the irradiation; statistical errors in counting were therefore of the order of 3%.

The counting rate of each foil in a set was corrected for decay using the decay curve of the monitor foil run with that set. An average counting rate was then determined for each foil, and ratios were taken to determine the flux distribution. In every case the flux at the center of one end of the cobalt was taken as unity, one foil being irradiated in this position in each run.

Curves giving the flux distribution are shown in Fig. 1. The curves involve a large amount of interpolation. Integration of the flux curves of Fig. 1 over the volume of source gives a value of 0.77 for the ratio of the average flux in the cylinder to the flux at the center of one end ($x = 0.375$, $z = 0$).

To determine the flux depression caused by the presence of the cobalt, a run was made in which the cobalt was replaced by a 2S aluminum cylinder of the same dimensions. Using the monitor foil to normalize to a run with cobalt, it was determined that the flux (at $x = 0.375$, $z = 0$) with cobalt present is only 0.58 as great as the flux with no cobalt.

The net effect of the self-protection and flux depression is that the activity of the cobalt would be only $0.58 \times 0.77 = 0.45$ of the activity calculated on the basis of a uniform, undepressed neutron flux. It is estimated that an error of about 6% is associated with the above number.

Large Source

For the work with the large cylindrical cobalt shells, the foils used were again copper, about ¼-in. diameter and weighing about 12 mg. In each run, the foils were selected so that the maximum variation in their weight was less than 3%. The foils were held in place on the cobalt source and aluminum dummy by Scotch tape.

The irradiations were carried out with the reactor power maintained constant at the desired level (of the order of a kilowatt). The cobalt source or the aluminum dummy, with foils in place, was inserted into the desired position in the reactor* and allowed to remain there for about 6 min. The source was then removed and the foils counted.

The reactor power level, held as constant as possible throughout the entire operation, was monitored by a BF_3 proportional counter located at an experimental hole far from the point of irradiation. The counting rate in this monitor was used to normalize the several runs in a set.

After irradiation, the foils were counted on end-window G-M counters, and the decay was followed for at least three half-lives of the short-lived activity. Counting rates were always greater than 3,000 cpm, 5 min after

* Several positions were actually used in the pile lattice and the reflector.

the end of the irradiation; thus statistical errors in counting were of the order of 2% or less. Where necessary, corrections were made for counting losses due to dead time in the G-M counters.

The decay curve for each foil was plotted, and the data used only if the decay constant appeared to be correct.* In several cases, data were discarded because the foils showed contamination by long-lived activities picked up by contact with the experimental hole. The information obtained from each run was the relative neutron flux at various positions on the source and dummy.

Because of the large size of the source and the more complicated geometry inside the lattice relative to the thermal column, it was necessary to carry out several sets of experiments. Although some of the measurements could have been avoided, they seem worthy of brief description.

Measurements in the lattice. This group of experiments was carried out at a reactor power of 400 watts in a 3-in. diameter channel in the graphite, lined with an aluminum tube of 2⅞-in. inside diameter. The channel runs parallel to the loading channels and is centered in the 8 × 8-in. square formed by them. The source or dummy was placed in the hole with its inside end positioned 18 in. from the gap at the center of the reactor.

During the irradiation, all the nearby fuel channels were loaded, and, in addition, several pounds of iron and copper were being irradiated at the extreme inner end of the hole, about 1 ft from the source.

The first run in this set was a check of the symmetry of the neutron flux around the experimental hole. Four foils were placed at equal intervals around the circumference of the cobalt source 6⅛ in. from its end. Within experimental error, all four foils showed the same activity. In all later runs, the cylinders were placed in the hole with the foils on the upper surface; however, no effort was made to do this with any great degree of accuracy.

The second run was a determination of the flux distribution in the cobalt cylinder. Six foils were used; three on the outside surface of the cylinder, the other three on the inside surface. These foils were located ¼ in. from each end, and 6⅛ in. from the ends.

The measured flux distribution is shown in Fig. 2, with flux at the outside of the cylinder, ¼ in. from the ends, taken as unity. The experimental points represent intensities on the inside and outside surfaces of the shell at various positions along the length of the cylinder. The results of the experiments on the small cobalt source were used as a guide in drawing the curves through the experimental points. The curve for $R = 1.00$ in. was interpolated assuming an exponential decrease of the neutron flux through the walls of the cylinder (see appendix); however, this assumption did not have much influence on the results.

Numerical integration of the flux of Fig. 2 throughout the volume of the cylindrical shell gives an average flux of 0.64 relative to the flux on the outside of the cylinder, ¼ in. from the end. It is estimated that this number is good to at least 10%. In the integration, it was assumed that, in the absence of the cobalt cylinder, the spatial neutron flux distribution was flat at the same location. This assumption was justified by the fact that the foils at the two ends of the cylinder showed the same activity, and, in addition, this assumption was verified experimentally in a later set of runs.

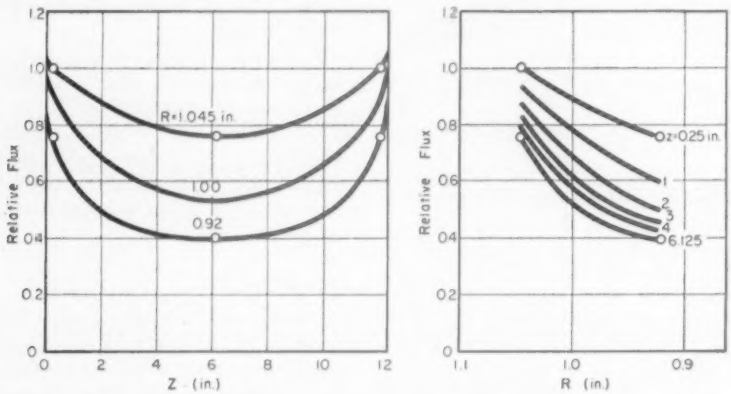

FIG. 2. Neutron flux distribution in large Co source as function of distance along cylinder and radial distance in cylindrical shell

Measurements in the reflector. This set was carried out in the reflector of the reactor, rather than inside the lattice itself. The objective was to determine the flux depression caused by the cobalt in a region where there were no other perturbing poisons. It was felt that the presence of strong absorbers near the sample in the position used for the measurements in the lattice might invalidate flux-depression measurements.

The experiments were carried out at a reactor power of 6 kw in experimental hole W-14. In this location, the nearest poison was 21 in. from the cobalt. Special graphite pieces were made to carry the cobalt or dummy so that they were completely surrounded by graphite. In addition, the rest of the experimental hole was kept filled with graphite. There was, therefore, no streaming of neutrons in the experimental channel. The graphite pieces also carried foils to measure the neutron flux far from the cobalt.

The copper foils were placed on the top surface of the cobalt cylinder or dummy at the same axial positions as in the first set of experiments. The results of a run with the cobalt and one with the aluminum dummy are shown in Fig. 3, the Al dummy run giving the unmodified flux distribution in the reflector, and the Co run the depressed flux. This figure also shows the location of the foils and source in the reflector.

The curves of Fig. 3 show that under the experimental conditions the flux at the ends of the cobalt is about 0.44 of the flux without the cobalt present. This number is good to about 10%. The experiment also showed that the neutron flux was not measurably perturbed at distances greater than about 14 in. from the cobalt sample used. In fact, the difference between the

* The actual half-life observed for the copper foils was 5.4 min. This is due to the sizable amount of 12.8-hr Cu^{64} activity present. However, since the decay appeared experimentally to be a single exponential for at least the first 10 min of counting, no attempt was made to separate these two periods.

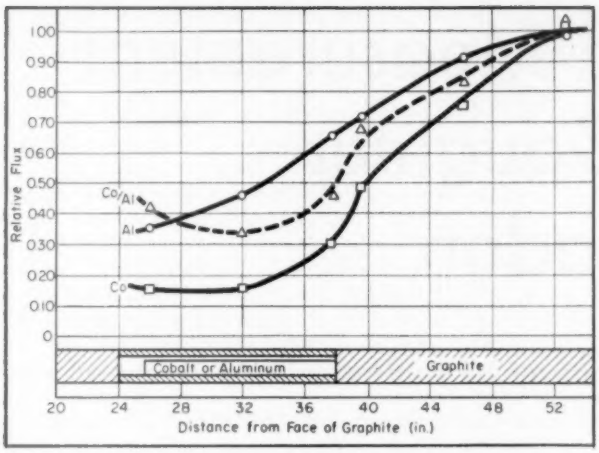

FIG. 3. Flux depression caused by large Co cylinder in reflector

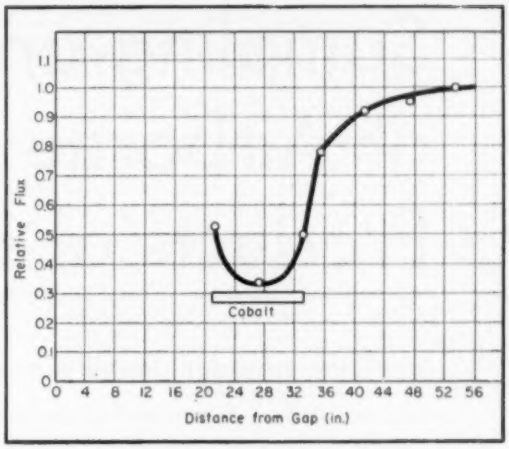

FIG. 4. Flux depression caused by large Co cylinder in center of lattice

dummy and the cobalt is about what would be given by diffusion from a negative source at the cylinder of strength equal to the cylinder's absorption.

Measurements in lattice; absorbers removed. This set of runs was carried out in the same hole as the other measurements in the lattice, but all absorbers other than fuel elements were removed from this region of the reactor. The experiment was designed to determine the flux depression caused by putting the cobalt source in the actual production location, where the unperturbed flux is flat. In addition to the three foils placed on the outer surface of the cobalt as before, four foils were put on an aluminum dummy that was irradiated at the same time as, and adjacent to, the cobalt. The results of this run are shown in Fig. 4.

A second run, using two aluminum dummies with foils in the same positions, showed that within experimental error the flux was constant over this region of the reactor. This result justified the assumption made earlier in calculating the average neutron flux in the cobalt source. From Fig. 4 it is seen that the flux at one end of the cobalt is 0.51 of the undepressed flux, within about 8%, about the same as the depression observed in the reactor reflector.

The final conclusion is that for production in the lattice the activity of the cylindrical cobalt source used would be only $0.5 \times 0.6 = 0.3$ of the activity calculated on the basis of a uniform, undepressed neutron flux. The result carries a probable error of about 10%. The reduction in effective flux is also about the same in the reflector as it is inside the pile lattice.

The results for the small solid cylinder and the large cylindrical shell show that serious reduction in source strength results from self-protection and flux depression. The reduction is actually much higher than would be expected from a rough estimate based on cross section and mean free path length of the neutrons in the sample. It is obvious that much higher activity for a given source size (a factor of 3 for the large cylinder) can be attained if the source is made up of smaller parts, which are assembled after a dispersed irradiation.

APPENDIX

In calculating the curve for $R = 1.00$ in., the cylindrical shell is assumed to be equivalent to an infinite plate of thickness, t, equal to twice the wall thickness of the cylinder. A neutron flux, I_0, is assumed to be directed inward along the normal on each side of the plate. At any depth, x, in the plate, the flux is then given by the sum of the contributions from both sides as

$$I(x) = I_0(e^{-\bar{\mu}x} + e^{-\bar{\mu}(t-x)})$$

where $\bar{\mu}$ is an effective absorption coefficient that takes into account the fact that, in reality, neutrons incident on the cylinder come from all directions, not just normal to the surface. Experimentally, $\bar{\mu}$ was determined from the ratio of the flux at $t/2$ to that at $t = 0$

$$r = \frac{1}{2}(e^{\bar{\mu}\frac{t}{2}} + e^{-\bar{\mu}\frac{t}{2}})$$

Using the experimental value for the ratio at a point 6⅛ in. from the end of the cylinder, a value of $\bar{\mu} = 10$ in.$^{-1}$ was obtained. As was expected, this value was somewhat greater than the quantity $A\rho\sigma/M = 8$ in.$^{-1}$, which would follow from the cross section, assuming only normal incidence. Similarly, I_0 (the inwardly directed part of the flux) was calculated from this data. In the units of Fig. 1, it was found to be 0.7 at a point 6⅛ in. from the ends of the cylinder. Calculating the flux at this same axial position for $R = 1.00$ in. ($x = 0.045$ in.), a value of $I(0.045 \text{ in.}) = 0.53$ was obtained. Using this calculated point, the balance of the curve for $R = 1.00$ in. was drawn as a reasonable interpolation between the other two curves.

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Sampling and Measurement of Airborne Daughter Products of Radon

Inhalation of radon daughter products can be more hazardous than inhalation of radon itself. A method is described for simple, rapid determination of radon and its daughters for concentrations as low as 5×10^{-15} curies/liter

By JOHN H. HARLEY
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FOR MANY YEARS it has been known that the measurement of airborne long-lived alpha emitters must be carried out after the short-lived daughters of radon collected with the dust have decayed.

Rough measurements made here indicated a correlation between the concentration of radon in the air and the activity of the short-lived radon daughter products. This indicated that the daughter-product activity could be used as a measure of both the radon concentration and the daughter products themselves.

Both fields of investigation require a knowledge of the behavior of the daughters in standard air-sampling techniques. This paper is the direct outgrowth of this need. It does not introduce a new method of sampling or analysis, but rather a method of interpreting daughter-product activities in a dust sample.

This process allows the determination of radon in air by a simple, rapid method and, at the same time, furnishes a measure of the daughter-product activity. Both of these are of value in assessing exposure of workers handling Ra-bearing materials.

The method offers many advantages for field work because of the speed with which results may be obtained. This is critical where studies of ventilation are being made, and where large numbers of samples must be analyzed.

The practical limit of detection for radon that this method affords is 5×10^{-15} curies/liter. This compares well with the 2×10^{-14}-c/l limit of the best standard ionization chamber equipment. Furthermore, the ionization chamber measurements are slow because of the time required for sample transportation, and the limited amount of suitable equipment available.

The major defect of the method lies in its dependence on the existence of radioactive equilibrium at the time of measurement. It is possible that either high ventilation rates or high, rapidly settling atmospheric dust loadings may very quickly reduce the concentration of airborne daughter products below equilibrium with radon. The probable maximum order of magnitude of this effect is a factor of 2. At any rate, the degree of nonequilibrium, and therefore the error, should

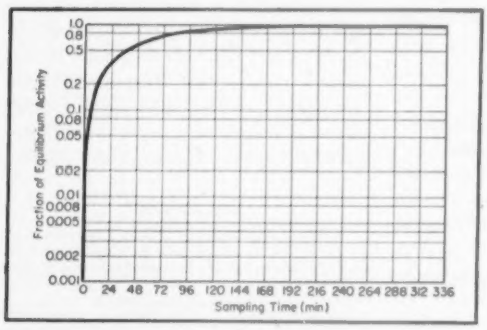

FIG. 1. Build-up of Rn-daughter activity on filter paper

TABLE 1—Characteristics of Radon Daughter Series

Isotope	$T_{1/2}$	λ (sec^{-1})
1. Rn^{222}	3.825 d	2.10×10^{-6}
2. Po^{218}(RaA)	3.05 m	3.79×10^{-3}
3. Pb^{214}(RaB)	26.8 m	4.31×10^{-4}
4. Bi^{214}(RaC)	19.7 m	5.86×10^{-4}
5. Po^{214}(RaC′)	1.5×10^{-4} sec	4.62×10^{3}
6. Pb^{210}(RaD)	22 y	—

The Hazard of Exposure to Radon and Radon Daughters

Workers engaged in the mining and processing of radium-bearing materials are exposed to dusts of the parent, to radon, and to the radon daughter products. Inhaled radioactive particulates may be retained in the lung or redistributed to other organs of the body. Relatively minute deposits of radioactive substances, particularly alpha emitters, have been clearly shown to be the etiological factor in a variety of injuries to industrial and research workers (*1*).

If the alpha emitters are redistributed from the lung, they will, because they are heavy metals, tend to be deposited in the bone. Their toxicological action would be expected to follow that of radium. A great deal of information exists on radium poisoning because of the deaths of a large number of women employed in dial painting in the early 1920's. Although the radium involved was probably ingested rather than inhaled, the mode of entrance is of slight importance compared with the final site and the amount deposited. At the present time, the accepted maximum permanent deposit of radium in the body is 0.1 μg (*1*, *2*). The tolerance amounts of many other alpha emitters have been set on the basis of the experience with radium. An excellent review of the literature on radium poisoning up to 1945 has been made by Silberstein (*3*).

If inhaled alpha emitters are not distributed to other organs of the body, they may affect the lung tissue. The high incidence of lung carcinoma in miners of the Schneeberg and Joachimsthal regions in Germany and Czechoslovakia has incriminated radon as a carcinogen, although there is some question that other materials, such as arsenic, may be involved. No measure of the uranium or radium exposures in these mines is available, but the average radon concentration reported (*4*, *5*) was 3×10^{-9} curies per liter of air. Consideration of this and other factors lead Evans and Goodman (*6*) to recommend 1×10^{-11} c/l as a safe level for radon and thoron contained in the air.

The tolerance value for radon includes the effect of the daughters only by inference. Reviews of the literature prepared by Jackson (*7*) and Lorenz (*8*) discuss only the radon and not the daughter-product hazard. A good evaluation would require a knowledge of the amount inhaled and the immediate and long-term retention by the lung of both the radon and the daughters.

Two studies relating to the daughter-product hazard have been made. Bale (*9*) calculated that the lung dosage due to daughter-product activity is about three orders of magnitude greater than that due to radon itself. Harley and Fresco (*10*) showed that the daughter-product retention in the respiratory system was of the order of 50%. Further work on the radon and daughter-product hazards is now being carried out at the University of Rochester Atomic Energy Project.

In evaluating the exposure of workers mining or processing radium-bearing materials, the hazard from the inhalation of daughter products is apparently much more serious than that from radon itself. The evaluation of daughter-product activity from the air dust samples is direct and should be done whenever radon exposure exists.

be negligible under the field conditions for which the method was designed.

Theoretical Development

The state of radon daughter products in the atmosphere is somewhat doubtful. The available evidence makes it appear that the ions attach themselves to dust particles in the air, probably by electrostatic attraction. Thus, the normal air-sampling and counting methods should be adequate for daughter-product measurements, provided proper corrections for decay are made. However, since the daughters of radon form a complex radioactive series, interpretation of the count obtained on a dust sample is quite involved. Therefore, mathematical expressions relating the radon concentration of the air to the alpha activity during sampling and during the decay of the sample were developed.

When airborne dust containing radon daughter products is collected on filter paper, the activity will increase to a sampling equilibrium value at which the rate of deposition is equal to the rate of decay of the activity. When sampling is discontinued, the activity will decay rapidly, reaching an effective half-life of 31 min after about an hour.

If the buildup and decay equations can be derived, four methods of evaluating the daughter products on filter paper are possible:

1. The sampling may be continued until sampling equilibrium is reached, and the alpha activity on the paper then measured.

2. The activity may be measured at a known time before sampling equilibrium is reached.

3. The total number of disintegrations during a sampling period may be measured.

4. The decay of the activity on the filter paper may be measured and the equilibrium activity obtained by extrapolation.

The first three measurements must be made while the sampling is still in progress; the fourth may be made after sampling is discontinued.

Assuming that radioactive equilibrium exists in the air being sampled, it is possible to calculate the alpha activity which should be present under all conditions of sampling and measurement. The measured activity may then be used to calculate the radon concentration.

The constants used in the derivations for radon and its daughters are given in Table 1.

If the radon concentration is Q atoms/liter and the air is sampled at v l/min, we may derive an equation of the Bateman type

$$\frac{D}{Qv} = 1.59 \times 10^{-4} - 9.45 \times 10^{-6}e^{-\lambda_2 t} - 3.47 \times 10^{-4}e^{-\lambda_3 t} + 1.97 \times 10^{-4}e^{-\lambda_4 t} \quad (1)$$

where D is the disintegration rate in dpm, t is the sampling time in minutes, and the subscripts refer to the isotope number in Table 1. This equation is plotted in Fig. 1 as fraction of equilibrium activity as a function of sampling time.

At sampling equilibrium (when t is

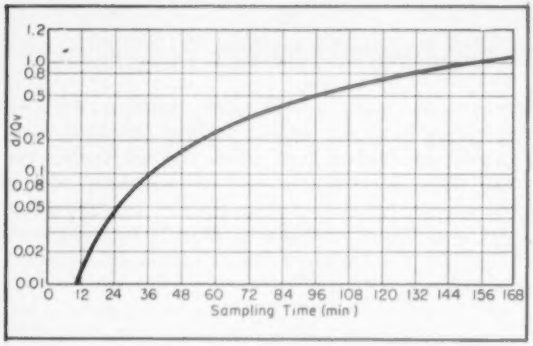

FIG. 2. Integrated radon-daughter activity on filter paper

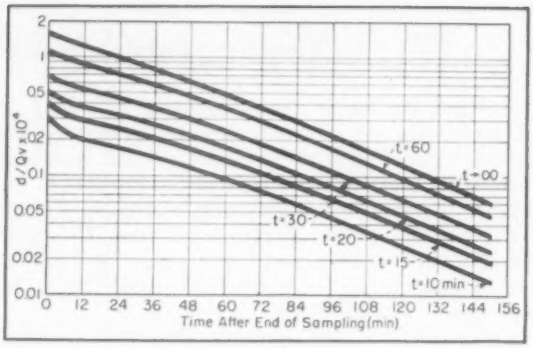

FIG. 3. Decay of Ra-daughter samples for different sampling periods

greater than 180 min) this reduces to

$$\text{curies/liter} = \frac{D(5.95 \times 10^{-15})}{v} \quad (2)$$

If sampling times less than that required for equilibrium are used, the appropriate fraction of the equilibrium value may be read off from Fig. 1, and the corrected value of D put in Eq. 2.

The total disintegrations during any sampling period may be obtained by integrating Eq. 1

$$\frac{d}{Qv} = -0.472 + 1.59 \times 10^{-4}t + 0.0025e^{-\lambda_3 t} + 0.806e^{-\lambda_2 t} - 0.337e^{-\lambda_1 t} \quad (3)$$

where d is total disintegrations. This equation does not approach a limit as t increases, so the values of d/Qv are plotted in Fig. 2 in absolute units.

The total disintegrations may be converted to radon concentration by

$$Q = (5.7 \times 10^{-17})d/Fv \quad (4)$$

where F is the value of d/Qv read off from Fig. 2 for the sampling time used.

The system of making decay measurements after discontinuing the sampling is the only method usable with standard equipment. The decay of the daughters is not purely exponential during the first hour but, after the initial period, the mixed daughters show a half-life of 31 min. If the decay rate of the sample is measured after the initial nonlinear period, the activity may be extrapolated back to the end of sampling by graphical methods. This extrapolated value is higher than the true value of activity (see Fig. 3), but the ratio, f, of extrapolated to true value can be calculated. These ratios for several sampling times are given in Table 2.

The extrapolated disintegration rate may be divided by this factor, f, to obtain the activity at sampling equilibrium. The corrected activity may then be substituted into Eq. 2 to give the radon concentration.

TABLE 2—Correction Factor for Sample Decay

Sampling time (min)	f
10	1.27
15	1.36
20	1.38
30	1.38
60	1.34
∞	1.16

TABLE 3—Comparison of Radon Methods

	Concentration (μμc Rn per liter)			
Run	*Equilibrium*	*Build-up*	*Integrated*	*Decay*
1	9.6	10.5	10.1	—
2	6.8	6.9	6.7	—
3	4.6	4.6	4.5	—
4	8.6	—	—	8.7
5	8.3	—	—	8.1
6	5.2	—	—	5.8
7	5.7	—	—	6.2
8	6.4	—	—	6.6

Experimental

The simplest method of sampling airborne dusts for counting analysis is by drawing air through a mechanical (fiber) filter. Measurement of the flow rate and of the sampling time allows calculation of airborne dust concentration from the results of analysis of the filter. The Health and Safety Division, New York Operations Office, AEC, uses a No. 41 Whatman filter for routine sampling, and this paper was used in most of the work reported here.

Alpha rather than beta measurement was selected because of the greater ease of alpha counting and because the alpha activity is of more direct value in evaluating daughter-product hazards.

The over-all technique has two major defects (a) the filter retention is low for submicroscopic particles and (b) the collection is not always at the surface, which allows the absorption of alpha particles by the paper. However, its simplicity and the possibility of making activity measurements while sampling led to its adoption.

The apparatus used consisted of a sampling head to hold the filter mounted directly over an alpha scintillation counter. The counting pulses were fed directly into a traffic recorder which printed the counts received during preset time intervals. Sampling was from a 1,000-ft³ room containing the radon.

The first measurements were made to test the validity of the derived equations. Counts were taken at 6-min intervals during the buildup of activity on the paper over a period of 3 hr. The fraction of the equilibrium value found for each interval was then compared with the calculated value. For both the simple buildup and the total disintegration methods, the average error was about 1%, showing the validity of Eqs. 1 and 3.

The three methods of evaluating radon concentration, measurement of activity at equilibrium, measurement during the sampling buildup, and the integrated measurement, were compared. Also, a comparison of the equilibrium method and the decay method was made. The results are given in Table 3.

The agreement between methods

was good, but the absolute values are only about 55% of the known radon content of the air sampled. The absorption of alpha particles by the filter paper has been estimated by Alercio and Harley (*11*) as 30% for uranium dusts. Although the retention of the No. 41 Whatman filter is known to be above 97% for industrial dusts (*12*), it was felt that the difference between the daughter-product measurement corrected for absorption and the true radon content might be due to lack of retention of submicroscopic dust particles carrying activity.

Simple retention measurements showed about 90% efficiency for the normal-room dust loading and about 97% efficiency for artificially dusty air. Therefore, the low results must be due to a higher absorption factor than previously found for uranium, or to the loss of daughter products on the chamber walls or on the sampling equipment. The reason for the difference cannot be proved absolutely, but, as it appears to be consistent, an empirical factor of 2 is chosen to correct for absorption, lack of retention, and daughter-product losses.

Molecular filters (Lovell Chemical Co.) were also tried to test whether the better retention and lower absorption would give more accurate results. The data for a series of runs (not corrected for absorption or retention) are shown in Table 4. The results are grouped according to the dust loading of the air into normal, low, and high dust. For low dust, the room and air were washed and the air filtered before the radon atmosphere was set up. For high dust, there were present about 10^7 particles per liter of NaCl, having a mass median of 1 micron.

From Table 4, it appears that the empirical factor of 2 is justified for normal and dusty atmospheres when using the Whatman filter. In low-dust atmospheres, such as might be found in air-conditioned laboratories, the retention of the submicroscopic particles is evidently poor, and a molecular filter should be used.

Holaday (*13*) has used the daughter-product method for evaluating radon in the mines of the Utah-Colorado region. The field measurements on the filters are made with an alpha survey meter, and an attempt is made to determine the degree of equilibrium which exists by counting during the early part of the decay period. This is possible because the shape of the nonlinear portion of the decay curve changes with degree of equilibrium.

The evaluation of the airborne daughter products themselves is, of course, direct and is not subject to errors due to the assumption of equilibrium.

A method similar to the one described is in current use in this laboratory for evaluating thoron and its daughter products.

TABLE 4—Results of Radon Analyses

	Concentration (μμc/liter)			
	Found			
Present	*Whatman*	*%*	*Molecular*	*%*
Normal dust				
0.10	0.05	50		
0.35	0.17	49		
11	5.9	54		
	5.6	51		
14	5.7	41		
	5.7	41		
	9.2	66		
	6.6	47		
260	144	55		
450	270	60		
	250	56		
Average		52		
Low dust				
29	2.5	9		
	2.4	8		
	2.4	8	12.3	42
	3.0	10	11.2	39
	2.6	9	13.4	46
	2.6	9	13.6	47
Average		9		44
High dust				
29			22.7	78
	13.5	46	17.6	61
	13.3	46	23.8	82
	14.2	49	23.3	81
	14.3	49		
	12.7	44	18.5	64
	14.0	48	20.8	72
	15.2	52	22.1	76
	15.4	53		
	16.9	58		
Average		50		73

* * *

This paper is abstracted from a thesis presented in partial fulfillment for the degree Doctor of Philosophy in Chemistry at Rensselaer Polytechnic Institute.

The work is the outgrowth of several related problems which have been studied in the laboratories of the Health and Safety Division. Many of the ideas have come out of discussions with members of the staff, particularly Merril Eisenbud, William Harris, Harris LeVine, and Evelyn Jetter. The author wishes to express his gratitude for their assistance and consideration.

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A Multiple-Counter System for Isotope Encephalometry

The multiple-detector positioner provides greater sensitivity for brain-tumor location than is possible with a single-detector method. Advantages are better reproducibility and detection of bilaterally symmetrical activities

By DOUGLAS A. KOHL
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DETECTION OF BRAIN TUMORS with radioactive I^{131} in isotope encephalometry is well known and rather extensively investigated from both the clinical and technical standpoints (*1–4*). However, technical improvements in detector efficiency and shielding systems have not resulted in an increase in clinical accuracy (*5–7*).

Clinical investigations have shown that the diagnostic accuracy of the technique using a single scintillation-counter detector approached 96% when the equipment was used by a neurosurgeon experienced in the counting technique (*8, 9*). The development of a multiple counter was an attempt to eliminate this dependence upon the skill and interpretive ability of the person conducting the test. It is hoped that such a system may be used to evaluate the physiological limitations of this isotopic method.

Multiple-detector Design

A practical necessity in the design of this system was the use of a number of detectors and decade scalers operating simultaneously to keep the total time for an entire head survey short enough to make a fixed-detector-position system possible.

The detector positioner, shown in the illustration, holds eighteen individual bismuth-cathode G-M tubes in their respective concentric lead shields. The shields are moved axially within close-fitting sleeves by means of separate hand-operated feed-screw mechanisms. The axes of the detectors intersect at a common central point and are arranged symmetrically, left to right and front to back. After the patient's head is oriented within the positioner, the detectors are advanced to maintain very light contact with the skull, thereby forming a cushioned holder for the head and maintaining a fixed orientation of the head within the detectors.

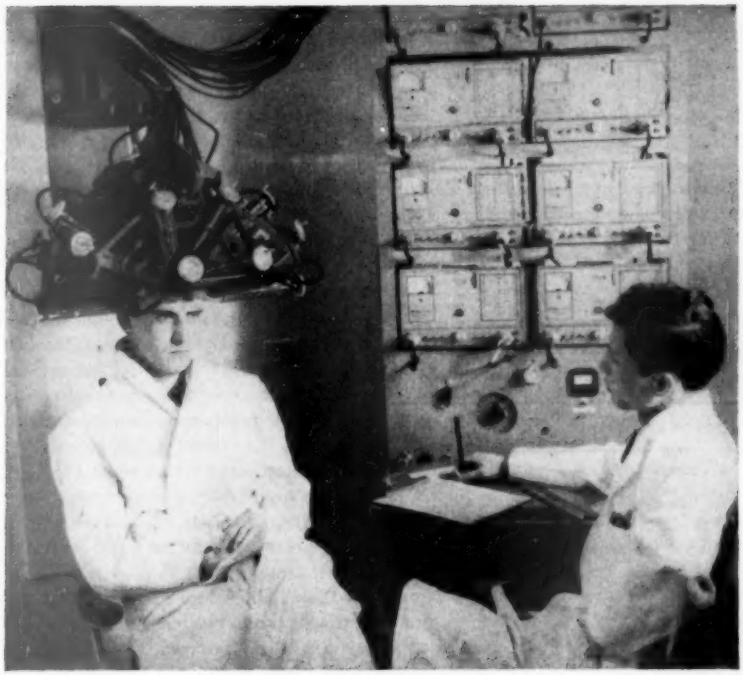
The eighteen detectors are counted in three groups of eight by the decimal scalers shown in the figure. Thus, the survey provides a total of nine symmetrical positions plus a recheck of three "significant" symmetrical positions. The scalers are gang-switched from one group to another between counting periods. The switch automatically furnishes the proper operating voltages for the G-M tubes and effects such a saving in time that the entire survey takes only 25 minutes, including the data recording time.

Initially each of the 18 G-M tubes was calibrated by comparing their sensitivities to an extended source of I^{131}. Each tube was given a correction factor which was derived from the sensitivity of the tube relative to the least efficient detector. This initial calibration was later checked in the positioner and corrected by the position averages of a large series of phantom skull measurements. Commercially available bismuth-cathode G-M tubes* were used, and the average variation in sensitivity to I^{131} was 7.9% when mounted in the shields.

Data Analysis

It has always been the standard procedure to utilize the anatomical symmetry of the brain as a normalizing factor and to compare, bilaterally, the activities of symmetrical positions. The relative difference in radioactivity level between a pair of positions is expressed as a percentage of the higher activity value. Diagnostic significance is attached to differential percentages

* N. Wood Counter Lab, Chicago, Ill. Standard 1-in. diameter × 5-in. bismuth cathode mounted in glass envelope without mounting base.



MULTIPLE-COUNTER system, using eighteen detectors and eight scalers

TABLE 1—Diagnostic Error Comparison

Clinical group classification	*Number of patients incorrectly diagnosed*		*Total number in group*
	Position-ratio analysis	*Differential analysis*	
Normal	2	0	4
Vascular abnormality	1	1	2
Tumors	4	10	17
Diffuse neurological abnormality	4	2	10
Localized neurological abnormality	Differential and position-ratio analyses are in agreement		9

TABLE 2—Analysis of Patient Missed by Differential Analysis

*Normalized position levels**		*Differentials*	
Increased activity (% deviation)	*Decreased activity (% deviation)*	*Left side (%)*	*Right side (%)*
A_L 7.8	C_L 10.1	C 2.5	A 4.6
A_R 12.4	C_R 7.6	D 1.3	B 4.8
F_L 17.3	D_L 7.7	E 2.9	G 7.9
F_R 16.9	D_R 9.0	F 0.4	H 5.1
I_L 9.6	E_L 13.1		I 1.9
I_R 11.5	E_R 16.0		
	H_L 12.5		
	H_R 7.4		

* Letters refer to detector positions. Subscripts indicate left or right.

that exceed an empirically established normal range.

This differential analysis is a practical system for head surveys with a single detector. Although the most obvious disadvantage of the method is its failure to detect symmetrically oriented bilateral abnormal activity, there are a number of other troubles inherent in the single-detector system. By far the major difficulty is that, unless some sort of positioning aid is used, there is apt to be a considerable error in reproducing measuring positions, both from the standpoint of attaining symmetry as well as establishing corresponding positions on different patients.

Multiple-detector method. With the fixed-axis-positioning system of the multiple counter, it is possible to expand greatly the amount of diagnostic information extracted from the data. Of importance is the fact that each symmetrical position pair has a definite activity level relative to every other pair. To isolate this information from variable factors such as dosage, injection-to-counting time, biological and radioactive decay, etc., the position relationships are expressed as ratios.

In practice, a simplification of the computation is made in order to avoid manipulating all of the 153 possible ratios. Eighteen normalized position levels are computed by dividing the position activity by the sum of all eighteen positions. In this way the position level is normalized with respect to the total amount of radioactivity within the head; it is assumed that the complete survey furnishes an accurate index of the total volumetric activity. Thus, the differential analysis, with its bilateral restriction for pertinent data, is a subanalysis of the position-ratio data.

Data Evaluation

The need for normalization is emphasized by a comparison of the multiple counter with the single scintillation detector used with a marked cap as a positioning aid (*10*). In a survey of 41 patients done with the scintillation counter, there was an average deviation in position levels of 24% after the dose factor variable was calculated out. This value dropped to 10% when the normalized position level process was performed.

The greater sensitivity of the posi-

TABLE 3—Measuring Instrumentation Comparison

Instrument	*Reproducibility error (average %)*	*Statistical error of counts (%)*	*Average over-all position deviation of patient groups (%)*	*Basic average deviation (%)*	*Total no. of patients*	*No. of tumors*
Scintillation counter (no cap)	7.6	1.1	....	...	20	1
Scintillation counter (cap)	3.5	1.1	10.5	6.5	41	10
Multiple counter	1.4	1.8	5.3	4.8	42	17

TABLE 4—Multiple-Counter Record of "Apparently Normal" Patient

*Normalized position levels**		*Differentials*	
Increased activity (% deviation)	*Decreased activity (% deviation)*	*Left side (%)*	*Right side (%)*
A_L 1.3	A_R 0.5	A 1.8	B 3.2
B_R 1.8	B_L 1.4	C 2.7	D 1.7
C_L 1.8	C_R 0.9	F 0.6	E 2.2
E_L 3.7	D_L 3.1	H 2.8	G 0.7
E_R 5.9	D_R 1.4	I 1.5	
F_L 0.1	F_R 0.5		
H_L 2.1	G_L 1.4		
	G_R 0.7		
	H_R 0.7		
	I_L 3.3		
	I_R 4.8		

* Letters refer to detector positions. Subscripts indicate left or right.

TABLE 5—Summary of Head Survey Position Deviations

	17 patients (tumors)	*25 patients (all others)*
Average deviation about the normalized position level	9.5%	8.4%
Average deviation of the correctly diagnosed cases about the normalized position level	9.5%	7.4%
Average number of positions per patient exceeding the average deviation	7.6 positions	5.6 positions
Average number of positions per patient exceeding twice the average deviation	3.6 positions	1.3 positions

tion-ratio analysis to tumors is shown in Table 1. In the case of the six additional errors in diagnosis of the tumor group when differential analysis was used alone, all but one were missed because of a symmetrical bilateral uptake of activity in the tumor. An illustration of this situation is shown in Table 2.

The information in Table 2 is a summary of the analysis of one of the patients missed by the differential analysis. All values shown in the position-level section are beyond the average deviations of the positions whereas none of the differentials exceed the average deviations. The relatively greater differential at position *G* was caused by right-side increase coincidently with a left-side decrease in the positions, neither of which exceeded the average deviation of the position-ratio group. The tumor was a very large and vascular meningioma occupying both frontal lobes as far back as the motor strip. The differential analysis must be adjudged normal, but both members of each bilateral position pair are very abnormal from the standpoint of their normal activity level.

It should be pointed out that due to the normalization scheme, the presence of a large amount of localized activity will give a number of positions apparent decreases in activity. This is not really a complication in that, in order for a diagnosis to be useful, the results must indicate a focal region of increased uptake which is very seldom found in the statistically produced abnormal values. If such a focus is obtained from those positions showing decreased activity, it is usually due to a space-occupying lesion which does not take up the tracer.

To illustrate the advantages gained through using detector-positioning devices, comparative factors are shown in Table 3. The data for the comparison were obtained from separate groups of patients with three investigators measuring their own specific group (*11*).

The reproducibility comparisons were computed from records of those patients that were counted several times with a number of hours intervening between measurements.

The average position deviation of patient groups was obtained by computing the average deviation of the eighteen positions about their average level for each patient and then combining all the averages in the group. Elimination of the reproducibility and statistical errors from the over-all deviations provides an index of the basic average deviations of the patient groups. Part of the difference in the basic deviations reflects the effect of the slightly different detector collimations.

The remarkably low basic deviation is reflected in the records of "apparently normal" patients. An example of such a record is shown summarized in Table 4. Only position E_R exceeds one-half the average deviation.

Clinical Results

A ruling enforced by the local radioisotope committee prevents the establishment of "true-normal" records for diagnostic reference. Consequently, the normal reference values were obtained by a series of approximations which tended to satisfy the following philosophy. Under the assumption that most detectable tumors have a

higher specific radioactivity than the brain tissue, the choice of normal values must simultaneously give the maximum number of abnormal indications in the known tumor group and the least number of abnormal indications in the remainder of the group.

With this idea, a set of normal position levels was found which also, incidently, closely matched the averages of the total group of 42 patients inclusive of 17 proved tumors. Each position possesses a distinct standard deviation due to the anatomical features under survey. The greatest deviation was found in the detectors on top of the head in close proximity to the saggital sinus.

The ultimate diagnostic result shows in the analysis in two ways. There is an obvious increase in the average position-level deviation of an abnormal patient due to the high levels of the detectors surveying the focal area, and, secondly, there are a greater number of positions exceeding the standard deviation. This information is summarized in Table 5.

On the basis of the indication of an abnormality somewhere in the head in the tumor patients and no abnormal indication for all other patients, the following results were obtained: 13 out of 17 tumor patients were correctly judged and 17 out of the remaining 25 patients were called normal.

Discussion

The fixed-positioning system, in addition to greatly enhancing the reproducibility aspect of the problem, adds more diagnostic information. The small patient sample (42) with only 17 tumors may not furnish a fair comparison between the position ratio and the differential analyses but it serves to emphasize the problem of symmetrical bilateral focii. It should be appreciated that position-ratio-analysis is advantageous from at least two other standpoints.

Differential analysis, due to its insensitivity to symmetrically oriented midline activity, may give a false focus if most of the tumor is midline and one end is skewed. Furthermore, occasionally a focal area may be oriented in such a way that some detector positions show a false differential due to some of the detectors picking up tumor contribution from the opposite side of the head. Such information is considered valid data and is correctly interpreted with the position-ratio system.

In practice, the separate normalization factors are retained in computing the position ratio and symmetrical results. The differential results are considered as secondary and used chiefly as a check against error.

A factor not included explicitly in the reproducibility errors of Table 3 is the effect of applying this system to the different cranial structures of various patients. This information is contained in the over-all position deviations and, within the limitations of the patient samplings, shows an important improvement in observing grouped patient records.

There is a considerable overlap of data in the normal and abnormal group classifications. As a result the data of those tumor cases missed are as normal as the "normal" category and the missed normals are as abnormal as the tumor group from every aspect. This is reflected in the insignificant change in the average deviations of Table 5 when the correctly diagnosed records are compared to the total group.

Although there is a significant difference between the standard deviations of the tumor group compared to the rest, the magnitude of the difference is relatively small and is one of the indications that the presence of most of the tumors did not substantially affect the counting levels of detectors not directly surveying the tumor site. Obviously this is a desirable characteristic from the standpoint of localization and much dependent on detector geometry.

A much "narrower" detector collimation is more practical with a positioner than without aids, but the usual recession of the effective counting center as a consequence of collimation is equally as important as restricting the field of sensitivity. The apparent counting origin of the detectors is 7 cm from the point of skull contact. Although no attempt was made to show this is optimal, the inverse-square variation of specific volumetric sensitivity is such as to permit a more uniform sensitivity to tumors at various depths than would be obtained with a detection volume in close proximity to the head.

In conclusion, it should be appreciated that the ultimate criterion for evaluating the clinical usefulness of the system is its ability to give a correctly oriented focus on the tumor site. An incorrect focus, although certainly indicative of an abnormal situation, must be considered as a negative result when attempting to categorize clinical studies. In the same way, an abnormal indication without a definite focus occurring in a normal patient would not be considered as indicative of anything.

To know the extent of the usefulness of this system, it must be ascertained whether a correlation exists between indicated focii and localized neurological indications. It is intended that a thorough diagnostic evaluation, together with a possible value for the physiological limitation of the diagnostic accuracy of this isotope technique, be published in a clinical journal.

* * *

Instrumentation of the multiple counter was sponsored by a grant from the U. S. Atomic Energy Commission. To Dr. G. E. Moore, director, Roswell Park Memorial Institute and assoc. prof. of surgery in the Buffalo School of Medicine, goes much of the credit for encouraging this study. Appreciation is also expressed to Drs. Chou, Johnson, and Haines of the Dept. of Neurosurgery, U. of Minn. Medical School, for their invaluable services.

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Ceramic Materials for Reactors

High-temperature operation of nuclear reactors is limited by the properties of available materials. Ceramics offer possibilities in ranges where metals cannot compete. The present status of research and application is shown by reports from several groups engaged in studying refractory materials

ALTHOUGH CERAMIC MATERIALS are currently serving as fuel, moderators, poison, shields and insulation in nuclear reactors, their full potential has not yet been realized. Research and development aimed at producing high-temperature materials with desirable nuclear properties was discussed at a recent meeting that included papers on refractories for nuclear power, properties of hafnium oxide, resistance to liquid metals, and cermets.*

Nuclear Power Applications

John M. Warde (Oak Ridge National Laboratory) pointed out that ceramics should not be directly substituted for metal shapes in reactor designs.

Since power reactors produce about seven times as much heat per unit area as a modern naval steam boiler, careful design is mandatory to prevent thermal stress failures. The major design factors to be considered are: adequate strength, thermal conductivity, thermal expansion, corrosion resistance, fabricability, neutron economy, radioactivity problems, radiation damage, utilization of high specific power, and fuel reprocessing.

Promising materials. The construction of high-temperature power reactors probably must await further development of ceramics. Physical properties, radiation stability, fabrication, ceramic coatings, phase equilibrium, and proper design for full utilization all require further study.

Use of ceramics in reactors up to the present time has provided some indication of their future usefulness. Among the available ceramic forms of nuclear fuel with high melting points are UO_2, 2,800° C; UC_2, 2,700° C; US, 1,700° C; U_2S_3 and US_2, 1,850° C; and USi_2, 1,700° C. Uranium metal, by comparison, melts at about 1,100° C.

Refractory ceramic materials having high neutron absorbing power include B_4C, HfO_2, and some of the rare-earth oxides such as those of gadolinium and samarium.

Other ceramic materials for general use as moderators, structural materials, and parts to resist abrasion, include Al_2O_3, BeO, MgO, HfO_2, ZrO_2, C, and SiC. In addition, ThO_2 is of considerable interest as a breeding material.

Hafnium Oxide

Carl E. Curtis *et al.* (Oak Ridge National Laboratory) in "Properties of Hafnium Oxide" pointed out that hafnia occurs as only ½ to 3% of zirconia, but is a better refractory material than zirconia. While minute quantities of hafnia have been available for 30 years, significant quantities of HfO_2 and pure ZrO_2 were not available prior to recent AEC-sponsored work on separation of the two materials.

Chemically, HfO_2 and ZrO_2 behave very similarly, but, as shown in Table 1, some of the other properties are quite different. Hafnia is a particularly interesting refractory as it is free of phase changes to at least 1,700° C, as compared to zirconia, which changes from monoclinic to tetragonal at about 1,000° C and can be stabilized in the cubic system by heating at higher temperatures with other oxides. In addition, it has a slightly higher melting point than zirconia and somewhat opposite nuclear properties. Hafnia offers many possibilities of usefulness as a crucible and reactor material.

Hafnium silicate ($HfO_2 \cdot SiO_2$), named "Hafnon" by Curtis and his coworkers, was synthesized and found to be very similar to zircon ($ZrO_2 \cdot SiO_2$). The compound $CaO \cdot HfO_2$ was likewise formed and found to be similar to $CaO \cdot ZrO_2$. In both of these hafnia compounds the atomic distances were found to be about 1% smaller than the corresponding ZrO_2 compounds. The thermal expansions were essentially the same.

Hafnium carbide was also formed. This was done at 2,500–3,000° C in an induction furnace by using the reaction $HfO_2 + 2C \rightarrow HfC + CO_2$. Hafnium carbide reportedly has a melting point of 3,800° C, the highest of any known material. One of the most interesting findings, however, is that its hardness was measured as 2,900 on the Vickers scale. The highest previously reported hardness for synthetically produced material is 2,400 Vickers for boron carbide.

Attack by Liquid Metals

The resistance of both metallic and ceramic refractories to attack by liquid metals that could be used for reactor coolants has been studied with a static and dynamic (convection harps) test apparatus by E. L. Reed (North American Aviation Inc.). This apparatus operates from 800 to 1,500° C. Results with sodium, bismuth and tin in liquid and vapor states are given in Tables 2, 3, and 4 for materials that stood up best.

In all of the static tests, the specimen was so mounted that about two thirds of it was covered by the liquid metal. The specimen was thus exposed to both the liquid and the vapor of the metal.

With sodium, some specimens showed color changes, but no appreciable change in weight. Spinel ($MgO \cdot Al_2O_3$), graphite, sintered poly-crystalline alumina, magnesia, and zirconia turned black or disintegrated.

* 55th annual meeting, American Ceramic Society, New York, N. Y., April 26–30, 1953. The papers on which this report is based were presented before the Refractories Division.

Clay-bonded silicon carbide stood up fairly well, but did not compare with the materials in Table 2. In bismuth, it crumbled at 1,000° C.

In tin, Vycor and TaC showed a little corrosion at 1,000° C. When exposed for one week at 1,000 and 1,500° C, Mo was badly attacked by tin.

Cermets

Development of cermets—combinations of ceramic and metallic materials—is directed primarily at jet aircraft applications, but these materials also offer promise for nuclear power applications.

Cemented chromium carbide. E. W. Engle and G. W. Lucas (Carboloy Dept., General Electric Co.) discussed this recently announced material. The most widely used composition, No. 608, consists of 83% Cr_3C_2, 2% WC, and 15% Ni binder. The Cr_3C_2 is prepared by reacting carbon with either chromium or chromium oxide. After mixing with the other ingredients, the powders are pressed, then sintered in a protective-atmosphere furnace.

The product has a specific gravity of 7, a hardness of 89 Rockwell A, and a modulus of rupture of 100,000 psi. By special processing, a product having a high degree of preferred orientation is obtained that shows even higher strengths along the axis of the grains. While cemented chromium carbide is intended primarily for use in corrosive media, it exhibits good hot strength as shown by tensile strengths of 46,000 psi at 1,200° F, 32,000 at 1,350° F, 16,000 at 1,500° F, and 3,500 at 1,800° F.

In a hot oxidizing atmosphere, an oxide film 2 microns thick forms to prevent further oxidation of the cemented chromium carbide. In other media, this material has shown excellent resistance to corrosion as well as abrasion.

Pressure-sintered dense silicon carbide. R. A. Aliegro and J. R. Tinkelpaugh (Alfred University) have prepared both pure silicon carbide and metal-bonded silicon carbide by hot pressing. By pressing at 8,000–10,000 psi and 2,300–2,450° C in graphite dies, pure silicon carbide having densities of 2.7–3.04 gm/cm³ (85–95% of theoretical) can be produced. This material has a reported hardness of 2,100–3,500 Vickers, considerably higher than the usual value of 2,000 Vickers reported for silicon carbide.

Numerous metals were tried as binders for a silicon carbide cermet. These include Fe, Ni, Cr, Mo, Co, Fe-Ag, Fe-B, Ni-B, and Cr-Mo. The first four were selected as being best after tests for reaction between silicon carbide and the metal. Cermets were hot pressed using 25–35% of the metal and 75–65% of SiC at pressures of 5,000–10,000 psi and temperatures of 1,600–2,000° C. The silicon carbide was grain-sized to provide good packing qualities and consisted of 60% 50–100 mesh, 15% 240 mesh, 25% 1,200 mesh.

Oxidation tests indicate that a very thin surface film is produced that protects the underneath portion so that at high temperatures about 1.5 mg/cm² is the maximum change in weight until equilibrium is achieved. While the work is still in progress, it has been shown that high-density silicon carbide and silicon-carbide-base cermets having good oxidation resistance can be produced.

Oxide- and carbide-base cermets. These materials have received a great deal of attention and have been the subject of many discussions as to their respective merits. In "High-Temperature Strength of Oxide-Base and Carbide Base Cermets and Related Physical Properties," E. T. Montgomery (Ohio State University) reviewed the requirements of a good cermet and the properties of the best (Al_2O_3 and TiC) of these two types. Factors on which to judge cermets include: high-temperature strength; chemical and physical stability; resistance to oxidation, thermal shock, vibration fatigue, and impact; and proper creep rate.

Available data indicates that while oxide (alumina) base cermets are stronger at high temperatures, they are not as resistant to thermal shock, vibration, and impact. They have thus been unable to pass Air Force thermal shock tests that consist of 1,000 heating and cooling cycles between 1,900° F and room temperature. Each cycle takes about 1½ min and is therefore a severe test. Titanium carbide base cermets, however, are being used in experimental gas turbines and appear to be quite successful. Both types of cermets should be useful for particular applications—the oxide base type where high hot strength is required, and the carbide base type where ductility and thermal shock resistance are more important.

TABLE 1—ZrO_2 vs. HfO_2

	ZrO_2	HfO_2
Atomic no.	40	72
Molecular wt.	132.2	210.6
Melting point (°C)	2,700	2,800
Density (gm/cm³)	5.68–6.10	9.68
Thermal expansion per °C	7–11 × 10⁶	(to 1,500° C) 6.45 × 10⁶

TABLE 2—Corrosion Tests in Sodium Liquid and Vapor

Material	*Temp. (°C)*	*Time (hr)*
Molybdenum	1,500	100
Tungsten	900	168
Tantalum	900	168
Alumina (synthetic sapphire)	900	168
Magnesia (single crystal)	925	168
Molybdenum disilicide (cast)	900	168
Thoria	925	168

TABLE 3—Corrosion Tests in Bismuth Liquid and Vapor

Material	*Temp. (°C)*	*Time (hr)*
Molybdenum	1,000 and 1,430	168
Tungsten	1,000	168
Phenium	1,000	168
Graphite (grades AUF and AWG)	1,400	168
Alumina	1,000	168
Magnesia	1,000	168
Zirconia	1,000	168
Molybdenum disilicide	1,400	168
Tantalum	1,000	168
Vycor	1,000	168

TABLE 4—Corrosion Test in Tin Liquid and Vapor

Material	*Temp. (°C)*	*Time (hr)*
Tungsten	1,000	40
Rhenium	1,500	840
Graphite (AUF)	cycled 800–2,000	1
Graphite (AUF)	1,500	840
Vycor	1,000	168
Chromium carbide	1,500	168

Dosimetry of a Kilocurie Cobalt-60 Source

Characteristics of four dosimeters were studied with the MIT cobalt-60 source:

FERROUS-FERRIC

Best for routine use; accurate, simple to use, reproducible results

CERIC-CEROUS

Accurate; requires careful application to obtain reproducible results

METHYLENE BLUE

Most simple in application but is less precise

ADIABATIC CALORIMETER

Not suitable for routine use; excellent for establishing yields of chemical dosimeters

By SOL DAVISON, SAMUEL A. GOLDBLITH, BERNARD E. PROCTOR, MARCUS KAREL, BILLY KAN, and CHARLES J. BATES
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EFFECTS OF IONIZING RADIATIONS on biological materials* are being studied here with a kilocurie cobalt-60 source, prepared by Brookhaven National Laboratory, as part of the AEC program concerned with utilization of fission products. To determine the energies absorbed by irradiated samples, three chemical dosimeters (ferrous-ferric, ceric-cerous, and methylene blue) and one physical dosimeter (adiabatic calorimeter) are being used.

The ferrous-ferric and the ceric-cerous dosimeters have been described by Miller (*2, 3*), Hardwick (*4*), Hochanadel and Ghormley (*5*), and Weiss (*6*), among others. The use of methylene blue as a dosimeter for high-intensity sources was developed in this laboratory and has been described by Goldblith, Proctor, and Hammerle (*7*). The adiabatic calorimeter used was modeled after one developed by Hochanadel and Ghormley (*5*) and was constructed by Dr. Sol Davison.

Although previous investigators have calibrated the chemical dosimeters mentioned in terms of yield for dose received, it was felt desirable, for two reasons, to use the calorimetric method as an independent physical check on the chemical methods.

1. There is evidence in this laboratory that equal doses, determined by chemical dosimetry, of γ-rays from cobalt-60 and cathode rays from a 3-Mev Van de Graaff generator do not have strictly comparable quantitative bactericidal effects on microorganisms (*8*). Confirmatory data regarding dose rates from these sources by means of physical dosimetry seemed desirable.

2. The precise inactivation dose of the methylene-blue dosimeter and the specific yields for the ferrous and ceric dosimeters are still somewhat in doubt.

Methylene-Blue Dosimeter

This dosimeter was the first to be used on arrival of the source. The observations of Goldblith, Proctor, and Hammerle (*7*) with a 3-Mev Van de Graaff accelerator (*9*) had demonstrated that aqueous solutions of methylene blue could be used as radiation dosimeters for high-intensity sources. The effective range extends from 25,000 rep_{83}* (at concentrations

* A survey of the literature pertaining to the application of ionizing radiations to the food and pharmaceutical fields has been prepared by the department, which discusses previous and current references (*1*).

Source and Shield Design

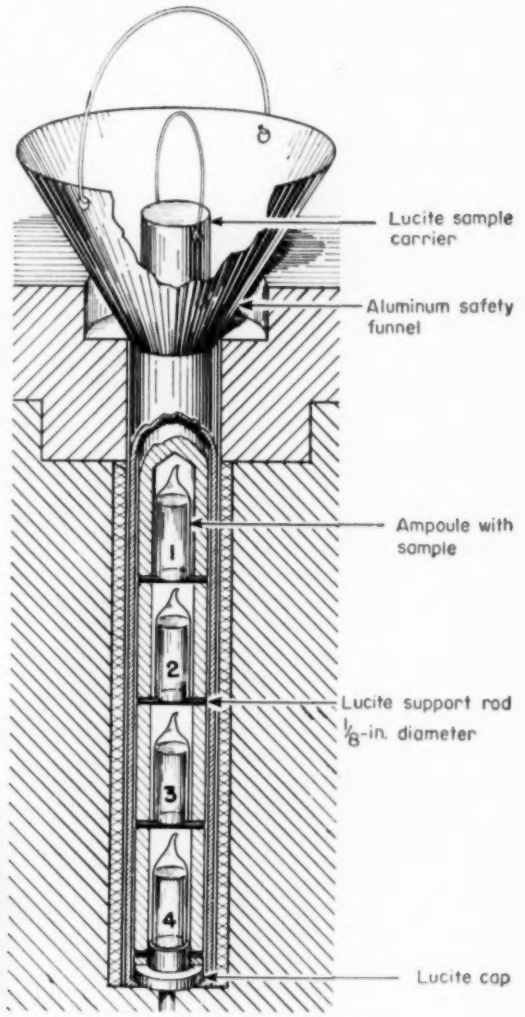
The MIT cobalt-60 source and shield has been described in detail by Manowitz (*13*) except for the numerical dimensions which are cited here.

The active metal is distributed uniformly in the form of two tubes placed end to end within two concentric aluminum tubes. A 2,300-lb lead pig encased in a stainless steel shell (diameter, 17 in.; height, 30 in.) equipped with a cover plug serves as a shield. The source with shield is contained in a concrete and steel vault (*14*). The vault is housed in the small concrete building shown below.

Access to the source is through a lead-steel door in the vault, set about a foot above the surface of the source-shielding pig. An operator at the barrier may pass samples through the vault door with a long pole for insertion into the source.

A cross section of the source in place in the shielding pig with the presently used arrangement for simultaneous irradiation of four liquid samples is shown at right. The aluminum funnel assembly serves both as a guide for insertion of the sample carrier and as a safety device. In the event of breakage of a sample, the contents are prevented from falling directly into the source and are easily recovered by simple removal of the funnel assembly.

The sample carrier was simply constructed from $1\frac{1}{4}$-in. Lucite rod with $\frac{1}{8}$-in. Lucite rods as spacers, to allow insertion of four ampoules.* In certain cases, steel cans of about 1-in. diameter are used for irradiation of materials in the source.† The cans are then loaded directly into the funnel assembly by means of a magnet attached to the loading pole.



** The ampoules used for the liquid samples were the thin-walled Kimble "Neutraglas" brand, of 5-ml capacity.*

† Cans were supplied through the courtesy of the American Can Company.

of 10 μg/cm^3) to 5,000,000 rep$_{83}$ (at concentrations of 1 mg/cm^3). The methylene blue undergoes an irreversible destruction, which can be assessed by colorimetric techniques.

The curve for the unchanged fraction as a function of dose has been found to be exponential. Hence radiation yield is conveniently expressed as relative to the inactivation dose, D_0 (*10*), which corresponds to the dose necessary to destroy all but a fraction, e^{-1} (37%), of the methylene blue in solution. The dose, D, received by the sample is

$$D = -D_0 \ln (n/n_0) \qquad (1)$$

where n_0 and n are concentration of methylene blue at the beginning and end of irradiation, respectively.

For determination of D_0, a calibrated source of cathode ray irradiation was the 3-Mev Van de Graaff accelerator. Doses delivered by this instrument were calculated from beam current and voltage measurements and previous data obtained by use of Victoreen ionization chambers. A simple average of the results from 72 samples (concentration 100 μg/cm^3), exposed to doses in the range 5×10^4 to 3×10^5 rep$_{83}$, gives the value $D_0 = 3.44 \times 10^5$ rep$_{83}$. The dose rate is then

$$\text{Dose rate (rep}_{83}\text{/min)} = \frac{3.44 \times 10^5}{t} \ln (n/n_0) \qquad (2)$$

where t is the time of exposure in minutes.

Ferrous-Ferric Dosimeter

The number of ferrous ions oxidized to ferric ions is linear with respect to dose. The yield is independent of concentration between $4 \times 10^{-5}M$ and $4 \times 10^{-2}M$ Fe^{++} and independent of wavelength from 100-kv X-rays to 2-Mev γ-rays. The yield also seems independent of dose rate from 0.02

* Two energy equivalents are commonly used for the rep, namely, 83 and 93 ergs per gram. Earlier reports from this laboratory have utilized the value of 83, whereas the more recent practice in the literature is to use 93. These values are designated as rep$_{83}$ and rep$_{93}$, respectively, when used in this paper.

r/sec to about 200 r/sec (*2*, *3*). There is a dependence of yield upon *p*H, which need cause no concern in the dosimetry if a definite *p*H is specified. An acid concentration that is 0.8*N* in sulfuric acid is the one commonly used. In the case of air-saturated samples irradiated in a closed system, the curve for ferric yield vs dose is linear up to about 50,000 rep. Weiss (*6*) indicates that a sharp break occurs at this point, and thereafter the curve continues linearly but at a reduced slope. The change is attributed to the consumption of oxygen.

Various methods are available for determination of ferrous and ferric ions. For example, ferrous ions can be titrated with ceric ions either potentiometrically or, by use of the orthophenanthroline complex at 510 mμ, photometrically. Ferric ion can be determined photometrically at 480 mμ by use of the thiocyanate complex, or directly at 305 mμ. The latter method of analysis was used throughout the observations with the ferrous-ferric dosimeter, a Beckman DU spectrophotometer being used at a slit width of 0.28 mm. The instrument was calibrated with known solutions of ferric ion in 0.8*N* sulfuric acid (*6*). A good linear curve of optical density vs concentration was obtained, which was used for subsequent analyses. The results of analyses of irradiated samples were corrected for the small amounts of ferric ion present prior to irradiation by similar analysis of the nonirradiated solution. There was no need to use solutions with ferrous concentration precisely known, because the analytical procedure requires determination of ferric ion only and the yield is independent of concentration.

The recent literature contains two experimental specific yields for the ferrous-ferric dosimeter, which are at appreciable variance with one another. The yield 20.2 micromoles per liter per 1,000 rep_{93} is supported by the observations of Hardwick (*4*, *11*) and Miller (*3*), both of whom applied the Bragg-Gray cavity principle to ionization chamber measurements. The yield 15.4 micromoles per liter per 1,000 rep_{93} was found by Hochanadel and Ghormley (*5*), who used both calorimetric and ionization chamber methods.

Ceric-Cerous Dosimeter

The number of ceric ions reduced to cerous ions is linear with dose. The yield is independent of concentration over a wide range ($10^{-2}M$ to about $2 \times 10^{-6}M$). The yield is independent of wavelength from 100 kv to 2 Mev γ-rays and independent of dose rate from about 0.5 to 500 r/sec (*4*). No difficulty is encountered with the consumption of oxygen in a closed system, as in the ferrous-ferric reaction.

There is no appreciable effect on the yield for the acid concentrations 0.8 to 1.97*N* in sulfuric acid. The concentration used throughout in these experiments was 0.8*N* in sulfuric acid. Also the smaller specific yield (about one sixth that of the ferrous-ferric system) makes this system more suitable for the higher dose ranges.

The ceric ion concentration may be determined by titration with ferrous sulfate or photometrically at 320 mμ. The photometric method was used throughout, a Beckman DU spectrophotometer being used at a slit width of 0.22 mm. The instrument was calibrated with solutions of ceric ion standardized by oxalate (*12*).

As ceric ion is determined by difference, it is important for matters of precision to adjust the concentration so that an appreciable fraction of the ceric ions is reduced. Concentrations were chosen that would give about a 50% reduction in the original concentration.

As with the ferrous-ferric dosimeter, Hardwick (*4*) differs from Hochanadel and Ghormley (*5*) in his experimental value for the yield of the ceric-cerous dosimeter. These values are 3.21 and 2.46 micromoles per liter per 1,000 rep_{93}, respectively. These are in the same ratio as the two values for the ferrous-ferric dosimeter. This would seem to indicate that the discrepancy in results lies in the physical determinations of energy. Weiss (*6*) has confirmed the ratio of yields, Fe^{+++}/Ce^{+++}, obtained in both cases.

The glass ampoules used in other radiation runs were not found suitable for the ceric-cerous dosimetry, as results obtained could not be reproduced when such ampoules were used. Comparable Pyrex ampoules improved this situation considerably.

Calorimetric Determination

Absorption of ionizing radiations by a condensed medium results in conversion of a large part of the total absorbed energy to thermal energy. In the case of water, the conversion

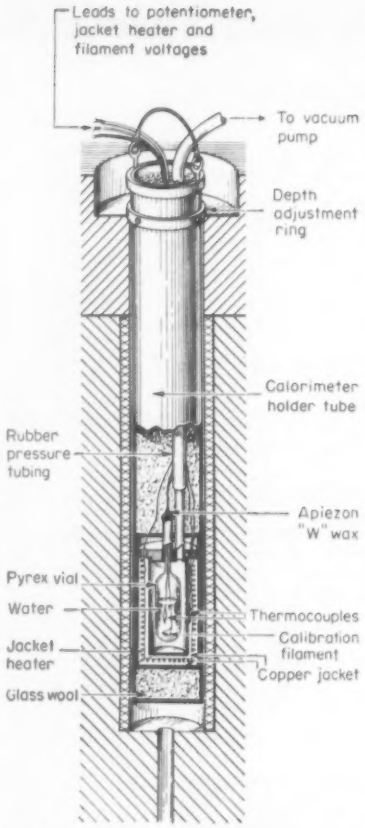


FIG. 1. Calorimeter in place in source

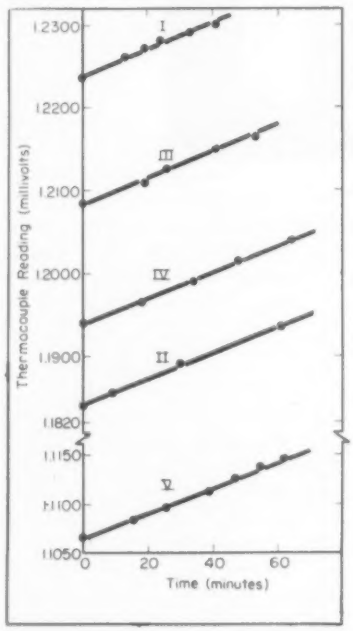


FIG. 2. Thermocouple readings obtained in five runs with the calorimeter

TABLE 1—Rate of Rise in Temperature of Water in Calorimeter

Run	*Duration of run (min)*	*Rate of rise of thermocouple readings [(mv/min) × 10⁴]*	*Rate of rise in temperature of water (°C/min)*
I	41	1.58	0.00384
II	61	1.59	0.00386
III	54	1.58	0.00384
IV	64	1.56	0.00379
V	62	1.55	0.00377

can be made quantitative by attaining an equilibrium state wherein products react to form water at the same rate at which they are produced. The net heat of reaction is then zero, and all energy actually absorbed by the water is converted into heat.

If the water is thermally isolated, its temperature will rise at a rate determined only by the rate of absorption of energy and the heat capacity, expressed thermodynamically as

$$dT/dt = (1/C_H) \times (dH/dt) \quad (3)$$

where H is thermal energy, C_H is heat capacity of the system, t is time, and T is temperature.

As the source of radiation is a radioactive isotope with half-life much greater than the interval of observation, dH/dt is essentially constant for constant geometry of the system. Therefore, if the observation is made over a small range of temperature where C_H for water may be taken as constant, the derivatives in Eq. 3 can be replaced by corresponding delta quantities representing discrete changes

$$\Delta T/\Delta t = (1/C_H) \times (\Delta H/\Delta t) \quad (4)$$

The rise in temperature is linear with respect to time under these conditions.

On the assumption that 1 rep is equivalent to 93 ergs per gram of water, and as 1 calorie is the equivalent of 4.18×10^7 ergs, it follows from Eq. 4 that the dose rate received by the water is given by

$$\text{Dose rate } (\text{rep}_{93}/\text{min}) = \frac{4.18 \times 10^7}{93} \cdot \frac{C_H}{W} \cdot \frac{\Delta T}{\Delta t} \quad (5)$$

where C_H is the heat capacity of water in calories per degree Centigrade, ΔT is the number of degrees Centigrade rise in temperature in an interval of Δt minutes, and W is the weight of the system in grams.

Equation 5 shows that a dose rate of 1,000 rep_{93}/min will produce a temperature rise in water of about 0.13° C/hr at room temperature. Temperature changes of this magnitude require application of careful calorimetric techniques. The adiabatic type of calorimeter used here is suited to these experimental conditions, i.e., a slow linear rise in temperature with time.

The calorimeter employed, modeled after one developed by Hochanadel and Ghormley (*5*), who used it to calibrate the ferrous-ferric actinometer with a 300-curie cobalt-60 source at intensities of about 25 and 75 r/sec and a 3,000-curie cobalt-60 source at an intensity of about 225 r/sec.

Figure 1 shows the calorimeter. A chromel-wire heater is placed between two concentric cylindrical copper jackets. The water is contained in a thin-walled Pyrex bulb placed within the inner jacket. The stem of the glass bulb is closed with wax to prevent escape of product. The wax also seals the inner jacket to the stem and permits good evacuation. Copper-constantan thermocouples placed in contact with the water and the inner jacket permit continual readings of temperature. A small resistance filament placed in the water enables a check on the performance of the instrument. A Leeds and Northrup No. 7552 potentiometer is used in conjunction with a Rubicon Spotlight galvanometer of 0.0007 μa/mm sensitivity. To maintain adiabatic conditions, the temperature of the interior jacket is kept equal to that of the water. Furthermore, thermal leaks by conduction and convection are held to a minimum by evacuation of the air space between bulb and jacket and small-gage thermocouple wires.

The best results were obtained by allowing the calorimeter to remain in the source without vacuum for several hours, to attain thermal and chemical equilibrium. After evacuation, the temperature of the water was recorded every fifteen minutes. Between readings the temperature of the interior jacket was kept equal to that of the water by manual adjustment of the jacket heater current with a Variac, so that a zero net potential was obtained from the two thermocouples wired in opposition. Thermocouple potentials were recorded to the nearest half microvolt. To minimize extraneous effects on potentiometer reading from contact potentials in the circuit, the scale of the galvanometer was adjusted for zero reading prior to each reading with thermocouples shorted.

TABLE 2—Dose Rates of Source (position no. 4; normalized to Jan., 1953)

Dosimeter and yield used	*Dose rates × 10⁻⁸*	
	rep_{93}/min	*rep_{93}/min*
Ferrous-ferric		
15.4 μM/l/1,000 rep_{93}	2.11	1.88
20.2 μM/l/1,000 rep_{93}	1.60	1.43
Ceric-cerous		
2.46 μM/l/1,000 rep_{93}	2.22	1.98
3.21 μM/l/1,000 rep_{93}	1.67	1.49
Methylene blue		
$D_0 = 3.44 \times 10^6$ rep_{93}	1.90	1.69
Calorimeter	1.62	1.45

Reagents

Reagent grade ferrous ammonium sulfate (Baker's analytical reagent) was recrystallized from water. Reagent grade ceric sulfate (G. F. Smith Chemical Co.) was used throughout. The methylene blue (Allied Chemical and Dye Co.) was used without further purification. Water used in initial runs was redistilled over permanganate. Later runs, made with water purified

by ion exchange to give the equivalent of triply distilled water (Deeminac Water Purifier, Crystalab, Hartford, Conn.), showed no detectable change in results. All chemical dosimeter runs, except the ceric-cerous, were made in the 5-ml Kimble ampoules.

Results

Figure 2 shows plots of thermocouple readings versus time for five runs with the calorimeter used to calibrate the cobalt-60 source. Only the linear portions of the temperature-time curves were selected for calculation. The different curves show a fairly constant slope for several temperature ranges in the interval 30.9° to 37.9° C.

To verify the observation that the temperature rise was a true consequence of radiation absorption and not the result of possible leaks in the calorimeter, a calorimetric run was duplicated outside the source with the assembly thermally insulated. No temperature change was observed under these conditions.

Table 1 presents data obtained on the experimental rise in water temperature with time ($\Delta T/\Delta t$) for the five runs. Millivolts were converted to degrees Centigrade by the factor 1° C = 0.0411 mv.

The average rate of temperature rise for the five runs, obtained by the weighting of each rise with respect to the duration of the run, was

$$\frac{\Delta T}{\Delta t} = 0.00381° \text{ C/min} \qquad (6)$$

The weight of glass used in the effective portion of the bulb was about 0.44 gm, whereas the weight of water was 3.03 gm. Therefore, the heat equivalent of the calorimeter, C_H, was $(3.03 \times 1.00) + (0.44 \times 0.2) = 3.12$ calories/°C, the specific heats of water and Pyrex being taken as 1.00 and 0.2, respectively.

The results obtained with the three chemical dosimeters and the calorimeter placed in the No. 4 or bottom position in the source are tabulated in Table 2. The results are normalized to January, 1953, by use of the known half-life of 5.26 years for cobalt-60. The ferrous-ferric dose rate is an average calculated from the results for 25 different samples irradiated at time intervals from 5 to 20 min. The ceric-cerous value is an average calculated from the results for two samples irradiated for 60 min and two samples irradiated for 120 min. The methylene blue value is an average calculated from the results for 41 samples irradiated for time intervals of 15 to 120 min. The dose rates are calculated in the case of the ferrous and ceric dosimeters on the basis of the two yields current in the literature (*4*, *5*). Evidently our ferrous-ferric and ceric-cerous results support the higher yields, when compared with the calorimeter value.

Table 3 shows the results obtained for the four different positions in the cobalt-60 source, averaged from 15 separate runs with both the ceric-cerous and the ferrous-ferric dosimeters, to calibrate the source for the variation of radiation intensity with depth. There is a total variation in intensity from top to bottom in the source of about 10%, with the No. 4 and No. 1 positions receiving the greatest and least intensities, respectively. The increased intensity at the bottom position might be attributed to increased secondary effects at the bottom of the source.

Calculations for γ-ray absorption in the materials used show that the attenuation of γ-ray intensity should be about equal in the calorimeter and ampoule holder arrangements (*8*). This was confirmed by runs made with ferrous solution in the calorimeter itself, which showed essentially the same intensity as that received by ampoules in the same position. It is, therefore, possible to calculate the yields of the chemical dosimeters by use of the calorimetrically determined dose rate.

Table 4 summarizes the yields for the three chemical dosimeters as calculated from the calorimetrically determined dose rate. The density of the ferrous-ferric and ceric-cerous dosimeter solutions is taken as 1.02 gm/cm³. Evidently the yields for the ferrous-ferric and ceric-cerous dosimeters compare favorably with those found by Miller (*2*) and Hardwick (*4*, *11*). The fact that the ratio of yields, Fe^{+++}/Ce^{+++}, is the same as that found by Hochanadel and Ghormley (*5*) suggests that any error in the discrepancy between our results would lie in the physical and not the chemical determinations of dose rate.

TABLE 3—Radiation Intensity Distribution in Depth of Cobalt-60 Source

Position No.	*Dose rate relative to position 4*
1 (top)	0.89
2	0.95
3	0.99
4 (bottom)	1.00

TABLE 4—Dosimeter Yields Referred to Primary Determination of Dose Rate by Calorimeter

Dosimeter	*Yield*
Ferrous-ferric	19.5 μM/l/1,000 rep_{93}
Ceric-cerous	3.23 μM/l/1,000 rep_{93}
Methylene blue (100 $\mu g/cm^2$)	$D_0 = 2.60 \times 10^5$ rep_{93}

Summary

The results of this research support the yields for the ferrous-ferric and ceric-cerous dosimeters found by Miller (*2*) and Hardwick (*4*, *11*), namely, about 20 and 3.3μM/l/1,000 rep_{93}, respectively. Independent studies (*8*) on cathode ray dosimetry of a 3-Mev Van de Graaff accelerator tend to support these results. This is considered of importance in studies now being conducted in these laboratories on the comparative microbiological effects of high-energy γ-rays, X-rays, and cathode rays.

The importance of establishing reliable yields for the ferrous-ferric and ceric-cerous dosimeters is paramount. We are now planning experiments with ion chambers in an attempt to obtain independent confirmation of the calorimeter results.

* * *

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ZIRCONIUM:

A Structural Material for Nuclear Reactors

Processes for purification, production, and fabrication of zirconium metal have been developed, improved, and expanded to a near commercial scale. Extensive physical, chemical, metallurgical, and engineering data have been accumulated. Here is a review of information pertinent to reactor technology

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DURING THE PAST five years an intensive effort, sponsored in large part by the Atomic Energy Commission and the naval reactor program, has resulted in the development of zirconium as a structural material for nuclear reactors. A substantial part of the declassifiable information thus developed was presented in a recent three-day symposium.† This article reviews some of this information, selected because of its interest to the field of reactor technology.

REASONS FOR INTEREST IN ZIRCONIUM

Reasons—nuclear, chemical, and mechanical—for the interest in zirconium for structural use in reactors, particularly as applied to long-range, large-scale atomic power production, were discussed in a paper on "Zirconium and Nuclear Reactors" presented by the writer. The paper will be used as a source for this part of the discussion.

The interest in zirconium results from its very low thermal-neutron cross section, its exceptional corrosion resistance in certain environments, and its retention of relatively good strength at moderately high temperatures.

The properties of zirconium make it particularly useful in thermal reactors, especially if they are to be used for power production, where neutron economy and regeneration of fuel are important. Further discussion here is therefore limited to thermal reactors and to structural materials with low thermal-neutron cross sections.

An indication of the importance of utilizing low cross section materials can be obtained by developing and examining a tabulation comparing regenerative efficiencies with the potential fractions of uranium consumed in a hypothetical reactor. The regenerative efficiencies of most reactors are not available in the unclassified literature, but a value of 0.8 has been released for Argonne National Laboratory's CP-3 research reactor. We will assume a hypothetical reactor or reactor cycle that uses natural uranium (with 0.7% fissionable material), regenerates continuously at an efficiency of 0.8, and utilizes the plutonium thus developed until all the fissionable material, original and regenerated, is consumed. For the purpose of these calculations, then, we will neglect the critical mass requirements and buildup of reaction products. Then the fraction of the uranium consumed will equal the sum of the geometric progression

$$0.007 + (0.007 \times 0.8) + (0.007 \times 0.8^2) + (0.007 \times 0.8^3) + \ldots + (0.007 \times 0.8^\infty) = \frac{0.007}{1 - 0.8} = 0.035$$

Similar calculations, based on other regenerative efficiencies, have been made, and selected values are included in the table on the next page. This tabulation is obviously hypothetical for several reasons, among them being the fact that, according to the presently declassified values for fission and capture cross section of plutonium, the theoretically attainable regenerative efficiency in a completely thermal plutonium-regenerating reactor is lim-

* Operated for AEC by Union Carbide and Carbon Corp.

† Symposium sponsored by the American Society for Metals at the Western Metals Congress, Los Angeles, Cal., March 24–26, 1953. The papers will be published in full shortly in a special zirconium volume by the American Society for Metals.

Fuel Consumption vs Regeneration

Regenerative efficiency	*Fraction of uranium consumed*
0.7	0.023
0.8	0.035
0.84	0.044
0.94	0.12
0.95	0.14
0.98	0.35
0.99	0.7
0.993	1.0

ited to 0.95. The tabulation does, however, indicate the importance of relatively small increases in regenerative efficiency—particularly as this efficiency approaches unity—on increased utilization of fertile material.

One way of improving these regenerative efficiencies is by the use of low cross section structural materials. An illustration, based on the data of the table, can serve to point this out. Consider a reactor which regenerates and reuses plutonium and produces an excess of 95 neutrons, of which 10 are unavoidably lost for reasons other than absorption by structural material, for each 100 plutonium atoms fissioned. This leaves 85 neutrons for regeneration and for losses to structural material. If we now assume a given quantity of structural material, such as aluminum or zirconium, with a cross section of about 0.2 barn, which will absorb one of the 85 neutrons, the net regenerative efficiency will be 0.84, which, according to the table, will use up 4.4% of the total uranium.

On the other hand, if we assume an equivalent quantity of a high cross section material, such as an 18:8 stainless steel with a cross section of 3.0 barns, 15 of the available neutrons will be absorbed, the net regenerative efficiency will be 0.7, and only 2.3% of the total uranium will be consumed. Now, if we can in some manner eliminate the previously postulated loss of 10 neutrons, the regenerative efficiencies for the selected systems will become 0.94 and 0.8, and the fuel utilizations will become 12% and 3.5%, respectively. The significance of low cross section materials in thermal reactors for long-range plutonium power economy thus becomes apparent.

The emphasis in the foregoing discussion has been placed on long-range, large-scale power problems. Actually there are more immediate reasons for the use of low cross section materials in currently operating and proposed reactors. One of these is that excessive parasitic absorption requires increased fuel investment. Also, if too much parasitic absorption occurs, the attainment of criticality or a given power level may require that the fissionable isotope be enriched above its content in natural uranium.

In addition to a low neutron absorption cross section, other stringent demands are placed on structural materials and components in power reactor systems. These include: (1) mechanical strength and stability under the severe stresses resulting from high thermal gradients; (2) leak-tight reliability in high-temperature, high-pressure, corrosive, dynamic, and radioactive cooling systems; (3) resistance to mechanical damage by radiation; (4) limited formation of high-activity products by nuclear reactions; and (5) adaptability to simple remote maintenance and repair.

SOLUTION OF HAFNIUM PROBLEM

The accelerated program of zirconium development received its initial impetus in the winter of 1947–1948 from the determination, by Pomerance, Feldman, and others at Oak Ridge National Laboratory, that the thermal-neutron absorption cross section of zirconium is about 0.18 barn instead of the theretofore listed value of about 3.5 barns. These investigators further recognized the discrepancy to be due to the 1½–3% hafnium (whose thermal-neutron absorption cross section is about 115 barns) normally intimately associated with zirconium in its ore minerals and commercial products.

Not only do zirconium and hafnium occur in intimate association in nature, but they also exhibit a considerable reluctance to disengage themselves from that association in most chemical treatments. In fact, the difficulty of their chemical separation approaches that involved in isotopic separation. The technology for producing hafnium-free zirconium could not have achieved its present state of development had it not been for the development of economical methods for effecting substantially complete chemical removal of hafnium from zirconium and for further purification of the zirconium product.

Work on several such processes was begun in 1948. A successful method was developed and placed in pilot-plant operation in 1949 by the Materials Chemistry Division of Oak Ridge National Laboratory. This successful process, developed under the direction of G. H. Clewett, assisted by W. R. Grimes and W. M. Leaders, led to the first full-scale production of hafnium-free zirconium oxide. In 1950, the full-scale production unit was placed in operation by the staff of the Oak Ridge Electromagnetic Plant (Y-12). This plant obtains its feed material from commercial sources and delivers a high-purity, hafnium-free zirconium oxide product for less than $5.00 per pound.

The purification processes used in the plant involve two steps. The first step is the removal of hafnium to about 50 ppm. Certain of the data pertaining to this hafnium separation step remain classified and will not be discussed further here. The second step, removal of impurities other than hafnium, has been accomplished by two different procedures. Initially, removal of the impurities involved the precipitation of zirconium salicylate by addition of salicylic acid to a zirconium chloride feed, followed by filtration, washing, and roasting of the precipitate to give a pure ZrO_2 product. Subsequently, ammonium phthalate was substituted as a precipitant, and the precipitated zirconium phthalate, after filtration and washing, is treated with ammonium hydroxide to regenerate the ammonium phthalate. The resultant zirconium hydroxide is roasted to produce a zirconium oxide product.

For a time, a third step, chlorination, was employed to produce a zirconium chloride product, but the chlorination step is now performed elsewhere and is no longer a part of the Oak Ridge process. The purification step reduces such elements as Al, Ca, Cu, Pb, Fe, Si, Mg, and Mn to less than 50 ppm each, but it does not remove phosphorus or the alkali metals. The present plant capacity in Oak Ridge is in excess of 1,000 pounds per day of hafnium-free zirconium oxide. The plant can also produce a hafnium product containing less than 2% zirconium.

LOCATION OF RAW MATERIALS

Sources of zirconium raw materials were described in "Zirconium Ores" by Oliver C. Ralston (Chief Metallurgist, U. S. Bureau of Mines). The principal commercial mineral is zircon, the silicate, recovered largely from beach sands or stream beds where it has accumulated along with other heavy weather-resistant minerals as a residual product of weathering of the granite. Large tonnages of these beach sands occur on the Florida peninsula and are worked primarily for their titanium content, the zircon being obtained as a by-product. The total tonnage of the available sands has not been determined, but it is far in excess of the currently anticipated requirements for zirconium and its compounds. Other deposits known to contain zircon are beaches and gold-placer gravels in California, gold gravels of Central Idaho, beaches along the Oregon Coast, titanium-bearing beach deposits at Travencore, India and along the east coast of Australia, and the placer-tin sands of Malaya.

One other commercial zirconium mineral exists, baddeleyite, an impure ZrO_2, which occurs along with zircon in the diamond-bearing sands of Brazil. The zirconium minerals are separated from the gangue and from the associated heavy minerals by various combinations of gravity concentration, screening, and mechanical and electrostatic separation. Flotation has been used in a few instances.

PRODUCTION OF ZIRCONIUM METAL

Several processes are available or under development for the production of zirconium metal and alloys. S. M. Shelton and E. Don Dilling (U. S. Bureau of Mines) in "The Manufacture of Zirconium Sponge" described development of the magnesium-reduction process by the Bureau's laboratory at Albany, Oregon, and described the present practice for the production of zirconium sponge and ingot metal. Development of "Consumable-Electrode Arc Melting of Zirconium Metal," at the Albany laboratory was described by W. W. Stephens, H. L. Gilbert and R. A. Beall.

The Bureau of Mines process is an outgrowth of an earlier magnesium-reduction method initiated by Dr. William J. Kroll. Work on zirconium was begun by the Albany Laboratory of the Bureau of Mines in January, 1945, and 90 grams of zirconium metal was produced in February. By the end of that year, several pounds of metal per week were being produced for melting, fabrication, and laboratory investigation. By 1947, a small pilot plant was in operation that furnished the necessary information for the design of a 5,000 lb/week plant that began operation in 1949. Production facilities have expanded almost continuously as improvements have been made in processing techniques. The present sponge capacity of the plant is 270,000 lb annually. Hafnium sponge is produced as a by-product at a rate of 6,000 lb annually.

Shelton and Dilling described the methods and equipment employed to briquette purified zirconium oxide obtained from the Oak Ridge-developed processes and to effect chlorination of the oxide in a shaft resistor furnace. The zirconium chloride is recovered in a condenser, and is partially purified in this operation as well as in the subsequent reduction step. The purified chloride is sublimed in a reduction furnace and then passed over the surface of a bath of molten magnesium to produce magnesium chloride and zirconium metal plus residual excess magnesium. The magnesium chloride and excess magnesium are removed in a vacuum retort, and they leave a mass of zirconium sponge. This sponge metal is removed and separated into various grades, which are then analyzed and blended into melting-furnace charges.

Melting zirconium is a major problem, because, when molten, it reacts with every known crucible material. The first Kroll-process product was melted in graphite crucibles by induction or graphite-resistor furnaces. To eliminate carbon pickup, most melting is performed today in arc-melting furnaces, with water-cooled copper crucibles and helium or argon atmospheres; however, vacuum melting is feasible. Tungsten-tipped electrodes have been used, but for most melting, today, use is made of consumable electrodes of cold-pressed bars of sponge that are welded to form continuous electrodes. The ingot thus produced can be remelted as a consumable electrode to achieve still greater homogeneity.

Alloy additions are made in small amounts that are introduced periodically in melting the first ingot. Ingots as large as 450 lb have been cast to 10-in. diameters, and much larger ones can be made if requirements warrant construction of the larger equipment.

The hafnium separated in the purification step can be similarly converted to sponge and melted to ingot form.

Although zirconium powder is not used in the principal production processes, it does have some direct applications as a powder, and some potential applications in powder-metallurgy methods for the fabrication of zirconium metal and its alloys. The various methods for the production of zirconium powder were reviewed, described, and evaluated in "The Production of Zirconium Powder," by Herbert S. Kalish (Sylvania Electric Products, Inc.).

M. A. Steinberg, M. E. Sibert, and E. Wainer (Horizons, Inc.), in "The Extractive Metallurgy of Zirconium by the Electrolysis of Fused Salts," presented the results of an extensive investigation of the subject. They reported the development of a foundation for an extractive metallurgy process for the production of pure ductile zirconium using an inert atmosphere cell with an inert crucible anode bath containing K_2ZrF_6, previously purified by recrystallization and pre-electrolysis, and an operating temperature of 800 to 850° C.

Many thousands of pounds of zirconium ingots have been produced by arc-melting iodide crystal-bar zirconium, according to a paper, "Fabrication of Zirconium," by R. B. Gordon and W. J. Hurford (Westinghouse

REACTOR MATERIALS . . .

. . . are the subject of a continuing series of articles in Nucleonics. Beryllium was discussed in the May issue (p. 52); zirconium is discussed here; a status report on ceramics starts on p. 20 of this issue. Other materials will be covered in succeeding issues. —**The Editors**

Properties of Zirconium

Mechanical properties are not given because there is not enough unclassified engineering data consistently representative of current production.

Melting Point (° C)	**1,845 ± 25***
Allotropic transformation temperature (° C)	**863 ± 3‡**
Density at 20° C (gm/cm³)	**6.490 ± 0.001***
Specific heat (cal/mole/° C)	
25–100° C	**6.32***
αZr, 862° C	**8.03†**
βZr, 862–1,127° C	**7.27†**
Electrical resistivity, 0° C (μohm/cm)	**39.7***
Temperature coefficient of resistivity, 0–200° C (per° C)	**0.0044 ± 0.0001‡**
Modulus of elasticity	**13.9×10^6**
Linear coefficients of thermal expansion (per° C):	
X-ray: c-axis	**$10.3 \pm 0.5 \times 10^{-6}$§**
a-axis	**$4.5 \pm 0.5 \times 10^{-6}$§**
Rolled sheet:	
thickness	**$6.7–10.1 \pm 0.4 \times 10^{-6}$§**
transverse	**$4.8–6.4 \pm 0.4 \times 10^{-6}$§**
rolling	**$4.6–5.9 \pm 0.4 \times 10^{-6}$§**

Lattice constants¶

	a	c	c/a
αZr (C.P. Hex.)	3.23	5.14	1.60
βZr (BCC-850° C)	3.61		

* H. K. Adenstedt, *Trans. Am. Soc. Metals* **44**, 949 (1952).

† E. P. King, J. P. Coughlin, *J. Am. Chem. Soc.* **72**, 2262 (1952). [$C_p = a + bt + et^{-2}$. For αZr: $a = 6.83$, $b = 1.12 \times 10^{-3}$, $e = -0.87$. For βZr: $a = 7.27$.]

‡ F. W. Boulger, AECD-2726 (1949).

§ R. McGeary, B. Lustman, *Trans. Am. Inst. Mining Met. Engrs.* **3**, 994 (1951).

¶ R. W. G. Wyckoff, "Crystal Structures," vol. 1 (Interscience Publishers, New York, 1951).

Atomic Power Division). They stated that most of AEC's requirements during 1950 and 1951 were melted from crystal bar produced by Foote Mineral Company or Westinghouse. The iodide process is also known as the van Arkel or the de Boer-Fast process. It involves the formation of zirconium tetraiodide by reaction between iodine vapor and crude zirconium powder or Kroll process sponge, followed by the thermal dissociation of the zirconium tetraiodide on a hot filament of zirconium or tungsten. The zirconium builds up in crystal form on the filament, and iodine is released to react with more crude zirconium. A paper, "Some Aspects of the Iodide, or Hot Wire, Process for Manufacture of Zirconium," by W. M. Raynor (Foote Mineral Company), described experimental development, specifications for production procedures, and performance of a semicommercial, iodide-zirconium plant.

FABRICATION OF ZIRCONIUM METAL

In working out the technology for using a new material, one of the most difficult tasks is the development of methods for fabricating the material into reliable engineering components while retaining, or even improving, the structural properties of the materials. The paper by Gordon and Hurford also reviewed the development work of the past four years and described and discussed present practices in the hot and cold working and secondary mechanical working of zirconium.

The development of the present state of zirconium fabrication technology represents one of the major and most difficult accomplishments of the entire zirconium program. Much of the work was done at Westinghouse, with significant contributions coming from other laboratories under AEC sponsorship and experimental fabrication being carried out by several industrial companies. Argonne National Laboratory is among the participating organizations whose substantial contributions were acknowledged, although there was no paper in the symposium that directly reported their work.

Pure zirconium has a hexagonal, close-packed (alpha) structure at temperatures up to 1,590° F (865° C), above which the structure is body-centered cubic (beta). All wrought zirconium shows preferred grain orientation, but no fabrication difficulties resulting from this behavior have been reported. The metal is inherently fine grained. It is readily hot worked by forging or rolling where the metal is covered with a layer of oxide. Extrusion and drawing processes are more difficult since they require special lubrication to prevent seizing to the working surfaces, there being no protective oxide film available.

Depending upon the type of material and sizes of ingots and desired bars or slabs, forging temperatures may start at 1,400–1,900° F and finish at 1,100–1,500° F. For hot re-rolling to strip or sheet, the starting temperatures are 1,400–1,550° F, and the finishing temperatures are 1,100–1,300° F. The scale on hot-worked material is very tenacious and must be removed by sand or shotblasting, followed by a HNO_3-HF pickle. Hot extrusion, at temperatures from 1,380–1,825° F, is feasible, but special precautions are required to avoid seizure and welding to the dies and tools. The precautions involve encasing the extrusion billet in a steel can, or, more recently, using the Ugine-Sejournet process in which glass serves as the lubricant.

Zirconium tubing has been produced by extrusion, tube-reducing and cold drawing, as well as by inert-gas-shielded-arc welding of rolled strip. Rod and wire have been produced on conventional equipment by using appropriate temperatures, intermediate anneals where required between cold-reductions, and special lubricants.

Strip and sheet can be cold-rolled satisfactorily, slit, sheared, and blanked. Cans can be formed by deep drawing, impact extrusion, and by successive drawings with intermediate anneals. Recrystallization temperatures vary from about 835 to 1,020° F according to the material and extent of cold work. Annealing after hot working is generally performed in air at 1,300–1,550° F.

The usual grades of zirconium can be machined satisfactorily by all standard operations, but this zirconium is somewhat abrasive, particularly if oxide scale is present, and fairly high tool wear results. These grades work-harden rapidly with dull tools, and they build up on the tool under some conditions. Work-hardened chips scratch finished surfaces when dragged over them and must be thrown clear of the work. Light cuts and dry-machining create fire hazards because of the pyrophoric nature of the thin chips; in fact, constant precautions must be taken in all machining operations because of this fire hazard.

In connection with the study of the mechanical working and annealing of zirconium, W. A. Bostrom and S. A. Kulin (Westinghouse Atomic Power Division), in "Recovery of Cold-Worked Zirconium," presented results

of a study of the annealing kinetics of cold-worked zirconium, as determined by electrical resistivity changes in comparison with the results obtained by hardness measurements and X-ray diffraction studies. Some recovery occurred even at room temperatures, an appreciable amount at 100° C, and it was relatively rapid at still higher temperatures.

ZIRCONIUM ALLOYS

Conventional commercial alloys of other metals are largely the result of a long period of evolution and a vast amount of empirical investigation. In recent years, the science of metals has developed to the point that some of the effects of alloy additions can be predicted, but there is still no complete substitute for the determination of the simpler phase diagrams, concentrated experimental investigation of the more promising regions of these and the more complex multicomponent alloy systems, and the accumulation of engineering experience obtained in the actual use of such alloys.

The previously mentioned paper by Gordon and Hurford states that to date there has been no extensive application of zirconium alloys but that it is probable that a demand will arise for alloys with improved properties, including increased strength, that will require higher hot-working temperatures and heavier cold-working equipment. The presently considered alloys use a sponge zirconium base metal and a maximum total alloy content of about 2%.

Analyses of the application of the principles of metal science to the prediction of alloying tendencies resulting from additions made to zirconium were contained in, "A General Comparison of the Metallurgy of Zirconium with that of Better-Known Commercial Metals," by A. D. Schwope (Battelle Memorial Institute) and in an invited contribution prepared in the form of a discussion by P. C. L. Pfeil (Atomic Energy Research Establishment, Harwell, England) and presented by H. M. Finniston (Head, Metallurgy Division, AERE).

Of particular concern in the use of zirconium is its susceptibility to low-temperature notch-embrittlement under certain conditions. This was discussed by Schwope and in "Effect of Hydrogen on the Embrittlement of Zirconium and Zirconium-Tin Alloys," by W. L. Mudge, Jr. (Westinghouse Atomic Power Division). Mudge reported the embrittlement susceptibility to be independent of type of base material, tin content of alloy, and melting procedure, and principally dependent upon the hydrogen content of the material, coupled with the heat treatment given the hydrogen-containing material. Heat treatments that produce embrittlement susceptibility apparently result in the precipitation of a hydrogen-containing compound, whereas the hydrogen present remains in solid solution in material that has been heat-treated to eliminate the susceptibility.

Summarized briefly, the data obtained by standard Charpy V-notch impact testing of heat-treated materials indicated that:

1. The low-temperature embrittlement susceptibility can be largely eliminated by reducing the hydrogen content to less than 10 ppm, generally by vacuum annealing in the neighborhood of 1,800° F.
2. Precipitation and consequent embrittlement susceptibility can be developed in material containing 30 to 50 ppm hydrogen by slow cooling through the range from 600 to 500° F, and the precipitation can be suppressed by water quenching through this range.
3. Precipitation cannot be suppressed by water-quenching material containing more than 100 ppm hydrogen.

Rapid, precise methods developed and employed for the determination of hydrogen in this important investigation were described in "Determination of Hydrogen in Zirconium by the Hot Vacuum Extraction Method," by R. K. McGeary (Westinghouse Atomic Power Division).

The development of a new metal and new alloys requires the development of metallographic techniques for their examination. F. M. Cain, Jr. (Westinghouse Atomic Power Division) in "A Simplified Procedure for the Metallography of Zirconium and Hafnium and Their Alloys," described a chemical polish etch suitable for a 5-min sample preparation that does not include mechanical or electrolytic polishing and is suited to bright-field or polarized-light observation and a variety of other applications.

CORROSION RESISTANCE OF METAL AND ALLOYS

"The Corrosion Resistance of Zirconium and Its Alloys," one of the outstanding properties of the material, was the subject of a paper by Lex B. Golden (U. S. Bureau of Mines). The paper reported corrosion test behavior of three different types of metal: (1) graphite induction-melted, hafnium-containing, "ordinary-purity" metal; (2) graphite induction-melted, "high-purity" low-hafnium metal; and (3) arc-melted, "high purity" low-hafnium metal.

Most of the available test results were based on "ordinary-purity" metal, which showed almost complete resistance to organic acids and inorganic chlorides, with the exceptions of ferric and cupric chloride solutions. The latter produced an embrittlement type of attack.

Tests on the two types of "high-purity" materials showed the arc-melted material to have almost complete resistance to concentrated hydrochloric acid under pressure at 60 and at 100° C, whereas the induction-melted material was severely embrittled. Under similar conditions "ordinary-purity" samples disintegrated. The arc-melted material also showed superior corrosion resistance in red fuming nitric acid, in aerated 80% sulfuric acid, and in aerated 20% ferric chloride solution. The induction-melted, "high-purity" metal was superior in aerated 85% phosphoric acid and in fuming sulfuric acid.

With reference to zirconium alloys, Golden stated that they are not likely to be superior to the *pure* unalloyed metal, but that there are possibilities of using one alloying constituent to offset the detrimental corrosion effects of another in making zirconium alloys. On the other hand, additions of moderate amounts of zirconium may improve the corrosion resistance of other metals. He cited a 13.8% zirconium addition to titanium that produced a manifold increase in corrosion resistance over unalloyed titanium in 5% hydrochloric acid, 10% sulfuric acid, and 10% phosphoric acid. Similar results were obtained in 90% hydrogen peroxide. END

Nuclear Emulsion Techniques for the Measurement of Neutron Energy Spectra

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NEUTRON SPECTROSCOPY is of paramount importance in many phases of applied and basic nuclear research. Because of the sensitive way in which neutron cross sections vary with energy, neutron spectrum determinations are of particular importance to the design of nuclear reactors.

Measurements of neutron energies and intensities can now be made with sufficient precision to permit accurate determination and classification, with regard to total angular momentum and parity, of nuclear energy levels (*1*) and, in a more general sense, to give better insight into the mechanism governing nuclear disintegrations in which neutrons are emitted (*2, 3*). Quite often, less precise measurements of neutron energy distributions are also of considerable value. Such is the case in neutron cross-section measurements, where it is usually necessary to know not only the precise energy of the incident neutrons but also the magnitude and distribution in energy of the background neutrons. A case in point is the $Li^7(p,n)Be^7$ reaction, which was used as a monoenergetic neutron source for a good many years before it was discovered, by means of nuclear emulsions (*4, 5, 6*), that above 800 kev there is a significant contribution of neutrons corresponding to the 330-kev level of Be^7.

Neutron spectrum measurements are fundamentally difficult for two reasons. In the first place, neutron energies must be measured through a secondary process involving a charged reaction product. The number of neutrons detected is thus proportional to the product of two nuclear cross sections, one corresponding to the initial production of the neutrons, and the other corresponding to a neutron interaction in which a charged particle is emitted. Intensity is therefore very often a serious problem. The second difficulty arises when one is attempting to determine the number of neutrons as a function of energy over a wide energy interval and is due to the fact that efficiency of detection is a rapidly varying function of neutron energy.

A bibliography (*1–61*) on neutron spectrum determinations involving the use of nuclear emulsions is given at the end of Part 1 of this article.

DEVELOPMENT OF EMULSION TECHNIQUE

The developments in the photographic emulsion technique up to 1941 are summarized in a review article by Shapiro (*62*). Since that time very remarkable progress has been made. A rather complete account of the state of the art as of 1947, together with the basic principles involved and the possible applications of the technique, are given in a book by Powell and Occhialini (*17*). Since 1947 there have appeared review articles by Yagoda (*63*), who also published a book on the subject (*64*), Demers (*65*), Webb (*66*), and Beiser (*67*). A rather extensive survey of the nuclear emulsion technique was made by Rotblat (*68*), who managed, in a limited space, to give a remarkably complete account of the general aspects of the technique, the types and characteristics of presently available emulsions, processing and analyzing procedures, and most of the important applications.

The general principles and experimental procedures involved in making neutron spectrum determinations with photographic emulsions are quite simple. It is this simplicity, in addition to the small size, continuous sensitivity of the detectors, and permanency of the record, that imparts to the method much of its elegance and usefulness. Furthermore there are very significant advantages to be realized (especially by way of minimizing uncertainties from background, which is ever-present in neutron experiments and usually determines whether an experiment is feasible) in being able to determine the direction of the ionizing particle responsible for a given track. In virtually all applications of nuclear emulsions to neutron spectroscopy, use is made of the length and orientation of the tracks of charged particles to infer the energy of the incident neutrons, and the precision with which these quantities are measured determines the resolution of the method.

One of the major objectives of the present paper is, therefore, to give an account of the methods that have been developed for accurately determining the length and spatial orientation of the track of a charged particle in a photographic emulsion.

Of the various types of nuclear emulsions now available, those best suited to most neutron spectrum work are the Eastman Kodak NTA and NTB plates and the C2 emulsions of Ilford Ltd., London, England. Of

In a detailed review, measurement procedures for extended neutron sources are presented, together with and introduction to the discussion of point sources. A preliminary discussion gives specific emulsion processing techniques and evaluates available optical equipment

PART ONE

the Eastman plates, the NTB are more sensitive and preferable to the NTA plates in work with neutrons of energy greater than 10 Mev. Nuclear emulsions are regularly produced in layers up to 600μ thick on glass backings 1.25 to 1.40 mm thick. In this laboratory we use 200μ emulsions on 1 in. $\times$ 3 in. glass backings for most of our neutron work, with occasional use of 400μ layers for work with neutron energies in excess of 15 Mev. The maximum detectable proton energy in C2 and NTB emulsions is approximately 50 Mev.

PROCESSING NUCLEAR EMULSIONS

Although each manufacturer suggests adequate techniques for processing his emulsions, Dr. A. H. Armstrong and Mrs. M. Gibson, of this laboratory, have found that, for neutron spectrum work in which it is important to determine the sense of the particle producing the trajectory, the following developing procedures may be used to best advantage:

The 100μ and 200μ plates are developed by a combination of the two-solution method (*69*) and the temperature-development method devised by Dilworth, Occhialini, and Payne (*70*). The plates are first soaked in distilled water for 1 hr; during this time the temperature is lowered from 21° to 5° C. They are then placed consecutively in solution A for 50 min and in solution B* for 50 min, both solutions being maintained at 5° C.

Upon removal from solution B the plates are placed glass side down, on toweling at a room temperature of 22° C, and permitted to remain so for 10 min. The plates are then placed consecutively into a stop bath of 2% acetic acid for 15 min (at the end of which time the surface silver is removed by rubbing lightly with the finger tips), into neutral hypo for 4 hr (hypo changed every hour), acid hypo for 30 min, and finally into wash water for 2 hr. The acetic acid, hypo, and wash water are all maintained at approximately 22° C, and all solutions are agitated mechanically. The plates are permitted to dry at room temperature and 50% relative humidity while lying horizontally, emulsion side up.

Our method for processing 400μ plates follows closely the procedure of Dilworth, Occhialini, and Payne (*70*) as modified by the Naval Research Laboratories (*71*). It is outlined in the table on this page.

If the plates have been in a vacuum, or otherwise desiccated, there is a tendency for the emulsion to separate

TABLE 1—400μ-PLATE PROCESSING

	Initial temperature (° *F*)	*Final temperature* (° *F*)
100 min presoak in distilled water	70	40
50 min in developing solution A	40	40
50 min in developing solution B	40	40
20 min dry developing (see procedure for 200μ plates)	40	70
5 min dry cooling	70	40
100 min in 2% acetic acid	40	40
Remove surface silver		
22 hr in neutral hypo with agitation and continuous renewal of hypo*	40	40
24 hr in hypo with constant water dilution at the same rate as above	40	40
3 hr to raise the temperature	40	60
24 hr wash	60	60
30 min in 6% Flexogloss	40	40
1 week drying at 50% R. H.	75	75

* Agitation is performed by bubbling nitrogen through the solution. During the first 18 hr, neutral hypo is used, new hypo being added constantly while old hypo is flowing out. During the last 4 hr, acid hypo is added rather than neutral hypo. The rate of flow of hypo is such as to transfer each hour a volume of new (and old) hypo equivalent to one-half the volume of the bath.

* The formulas used for the two-solution technique (*69*) are as follows:

Solution A: 2.2 gm of metol, 48.0 gm of sodium sulfite, 8.8 gm of hydroquinone, 4.0 gm of potassium bromide, and water to make 4 liters.

Solution B: 800 cc of stock Kodak D-19, 3,200 cc of distilled water, and 32 gm of sodium carbonate.

from the glass backing. This so-called peeling may occur while the plate is being desiccated, during development or after development, even though the plate is stored at 68° F and 50% relative humidity. Peeling may be inhibited by coating the edges of the plate with collodion or clear lacquer. Dr. G. M. Frye, of this laboratory, has found that branding the edges of the plate with a hot wire at any stage of its history (before desiccation, before development or after development) greatly inhibits peeling.

OPTICAL EQUIPMENT FOR PLATE ANALYSIS

In most experiments using nuclear emulsions, the time involved in exposing and processing the plates is quite negligible compared to the time required for analyzing the plates. That this situation obtains is obvious from the fact that the data, as recorded in the processed emulsions, have the form of rows of grains of colloidal silver, each grain less than 1μ in diameter. These rows of black grains, which identify the trajectories of the ionizing particles, must be found with 100% efficiency and then measured with high accuracy. The plate analysis work thus requires precision optical equipment which permits rapid progress without undue nervous or physical strain on the observer. Since most of the scanning is done by people who have no particular aptitude for geometrical optics, the optical train should lend itself to accurate alignment in a reasonable time and, once aligned, should be unperturbed by small disturbances.

Microscopes

We use two types of microscopes in the Los Alamos nuclear-plate laboratory, the Cooke, Troughton, and Simms (CTS), type M4005, and the Leitz Ortholux.

CTS microscope. The outstanding feature of the CTS microscope is the precision mechanical stage with which it is fitted. This stage is mounted on ball bearings, spring-loaded to avoid "backlash," and activated by micrometer movements in the X and Y directions. The graduations of the micrometer heads make possible the reading of the position of the stage to an accuracy of somewhat better than 2μ. A superstage makes possible the setting of the beginning of a track on a given point in an eyepiece graticule. The measurement of the track is carried out by means of the micrometer screws. Finally, the return of the slide to its original position on the stage is accomplished by resetting the micrometer screws to their original settings. Depth measurements are made with the fine-focus screw, which is activated by a dial graduated in intervals corresponding to an objective and eyepiece motion of 1μ in the vertical direction.

Leitz Ortholux. The Leitz Ortholux microscope is optically the equivalent of the CTS and is even preferable in some respects. For example, the alignment of the optical train is simpler and less critical. Also the rigidity of the instrument is such that, once aligned, unusually rough treatment is required to misalign it to such an extent that more than half a minute is required to realign it.

However this microscope, as presently manufactured, has the very distinct disadvantage that the stage is not equipped with micrometer movements. This has been overcome by fitting the stage with a precision screw drive in the Y direction and a superstage consisting of a micrometer-driven ball-bearing assembly, which moves the plate in the X direction, and can itself be moved in the X direction by a rack and pinion. The superstage makes possible the measurement of a displacement in the X direction with an accuracy of 1.5μ in 100μ and 3μ in 1,000μ. Measurements in the Y direction can be made with comparable accuracy.*

Tracks less than 100μ in length are usually measured with a calibrated eyepiece graticule fitted into one of the eyepieces. Angles in the horizontal plane are measured with an eyepiece protractor or with an eyepiece graticule ruled into 100 squares. The eyepiece protractor has a graduated scale, which permits the orientation of the eyepiece to be read to a few tenths of a degree. However, the characteristics of the track usually preclude the alignment of the fiducial line to better than 0.5 deg. Depth measurements are made with the fine-focus screw, a mirror arrangement being used to facilitate reading of the graduations on the fine-focus adjustment drum. Figure 1 shows a photograph of a Leitz Ortholux microscope with these adaptations.

Optical Components

The optical components of a microscope used for neutron spectrum work

* The above stage adaptations were engineered and built for us by Erb and Gray, Los Angeles, Cal.

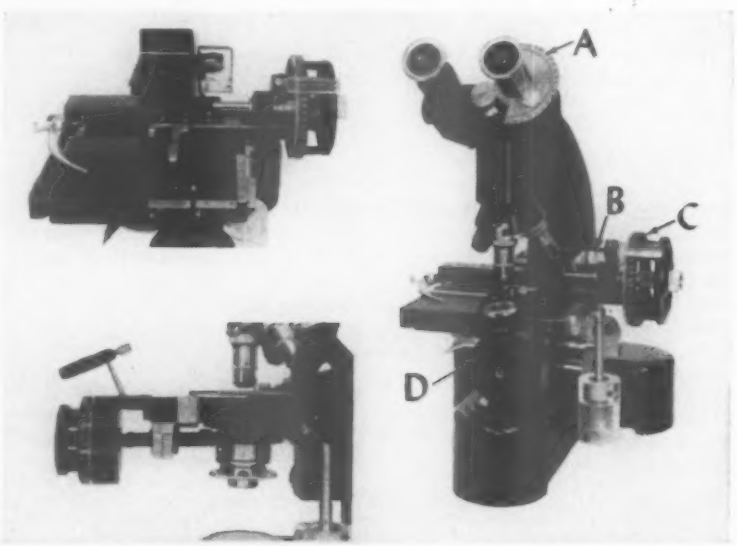

FIG. 1. Leitz Ortholux microscope as adapted for nuclear emulsion work. Insets show details of stage modifications

should be of high precision in both substage condenser and objective. Our microscopes are all of the binocular type with highly corrected substage condenser, apochromatic oil-immersion objectives, and compensating or periplan eyepieces. These components insure small depth of focus as well as adequate flatness of field. Most of our work is done with 60–120× objectives and 6× eyepieces; sometimes 45× oil-immersion objectives are useful.

The choice of high-power objectives is very often determined by the working distance.* Our standard high-power objective on the Cooke, Troughton, and Simms is the 80×, 2.2 mm, oil-immersion apochromat which has a free working distance of approximately 240μ.† The corresponding Leitz objective is the 92×, 2 mm, oil-immersion apochromat with approximately the same working distance. Both objectives have a numerical aperture of 1.3, which, however, cannot be realized unless the condenser makes contact with the plate through a film of oil. Since emulsions shrink by a factor of about 2.3 in processing, both of the above objectives are adequate for emulsion layers up to 400μ.

In addition to the standard objectives listed above, Cooke, Troughton, and Simms make a 3.75 mm oil-immersion fluorite objective (N. A. 0.95, mag. 45×), which has a working distance of 420μ. Leitz has recently developed some special objectives for nuclear plate work, among which are a 100× apochromat with a free working distance of 370μ and a 53× fluorite with a free working distance of 1,000μ.

The eyepiece under the operator's dominant eye is equipped with an eyepiece graticule divided into 100 squares. This graticule defines the area of the field of view and is calibrated with a Bausch and Lomb stage micrometer, which was ruled to an accuracy of 0.1% by means of interferometric methods. The second eyepiece contains a glass disk of optical path equivalent to that of the graticule. A line engraved along a diameter of this disk serves as a fiducial line when making measurements of angles in the horizontal plane. In calibrating an eyepiece graticule, it must be borne in mind that the calibration is a function of interpupillary distance.

Since both the CTS and the Leitz Ortholux microscopes have built-in illumination, we find it quite convenient to align the instruments for critical or Köhler illumination.

Depth Measurement

The most difficult measurement to make with a microscope of the types here described is the angle of dip of the track.

Oil-immersion objectives obviate the necessity for making corrections for the index of refraction of the emulsion, which is well matched by cedar oil. However, even with high-powered, high-numerical-aperture objectives, the depth of focus is approximately 0.4μ, and this sets an upper limit on the accuracy attainable in depth measurements.

Furthermore, one must be cognizant of the fact that the highly corrected apochromatic objectives are not free from curvature of the field. This means that depth measurements must be made on grains equidistant from the center of the field of view or at the same spot in the field. The latter method eliminates errors due to misalignment of the optical train.

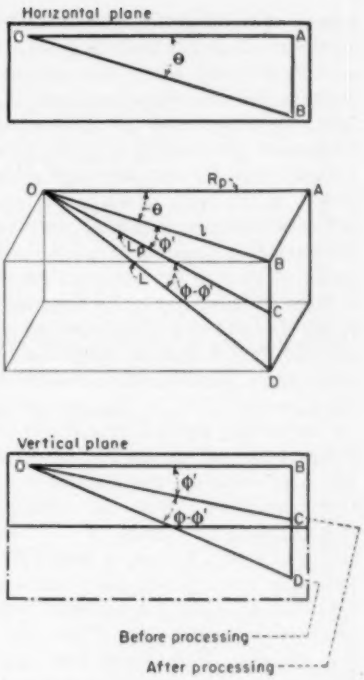

FIG. 2. Orientation of track in unprocessed and processed emulsion

EXTENDED ANISOTROPIC SOURCES

There are two general categories of neutron sources with which one is concerned in neutron experiments. These may be classified as extended, anisotropic sources, such as one finds inside a nuclear reactor, and point sources. The latter are, of course, much to be preferred from the standpoint of neutron energy measurements.

Proton-Recoil Method

To the best of the author's knowledge, the first reasonably successful attempt to measure the distribution in energy of the neutrons from an extended anisotropic source, using photographic emulsions, was made by Nereson and Reines (*72*). These investigators attempted to measure the neutron spectrum inside the Los Alamos fast reactor.

The method adopted for these measurements was, in principle, the same as that used by Zinn and Szilard (*73*) with ionization chambers In the experiment of Nereson and Reines, nuclear plates were exposed inside the fast reactor. After processing, the procedure was to measure all recoil proton tracks that were completely contained within a given volume of emulsion.

The flux of neutrons per unit energy interval is then given by

$$F(E) = \frac{AE}{n\sigma_{n-p}(E)} \frac{dN(E)}{dE} \qquad (1)$$

where A is the plate area analyzed, n is the number of H^1/cm^2 of emulsion, and $N(E)$ is the number of protons (corrected for their probability of leaving the emulsion) in unit energy interval at energy E, and σ_{n-p} is the n-p scattering cross section at the same energy.

Figure 2 illustrates the geometry involved in the determination of the

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* Other considerations are:

1. For oil immersion systems in which the numerical aperture ($N.A.$) of the condenser $\geq N.A.$ of objective, the depth of focus in microns $\cong (250/M \times N.A.) + (2.5 \times 10^3/M^2)$, where M = total magnification.
2. The magnification of an inclined binocular microscope of the types here described $\cong 270 \times M_{eyepiece}$/focal length of objective (mm).
3. Limit of useful magnification $\cong 10^3 \times N.A.$
4. Resolution in lines/cm $\cong 2 \times N.A./\lambda$ (cm) or $2.7 \times 10^3 \times M_{eyepiece}$/focal length of objective (cm), whichever is smaller.

† Free working distance is here defined as the processed emulsion thickness through which one can view with a given objective.

energy of recoil protons. The length of the recoil-proton track is given by $L = R_p \sec\theta \sec\phi$ where the notation refers to the unprocessed emulsion, R_p being the projection of the track in the horizontal plane along a given axis (usually parallel to the long plate axis). ϕ, the angle of dip in the unprocessed emulsion, is related to ϕ', the corresponding angle in the processed emulsion by $S = \tan\phi/\tan\phi'$, where S is the shrinkage factor for the emulsion. The energy of the proton can be inferred from L and the range-energy relation for protons in the emulsion being used (*74–76*).* The correction for the varying probability of tracks of different lengths leaving the emulsion can most easily be obtained for each track measured from the relation $P = (L_p \sin\phi')/t$ where P is the probability that a track of length L_p, making an angle ϕ' with the plane of a processed emulsion of thickness t, will penetrate one or the other of the emulsion surfaces. This implies that each track that is completely contained within an emulsion volume of thickness t represents $t/(t - L_p \sin\phi')$ tracks of equal L_p and ϕ' and implicitly assumes that the tracks are rectilinear, an assumption which, as we shall see later, is not quite justified. However, this assumption introduces negligible error when the track lengths are small compared to the emulsion thickness.

Difficulties of method. This method of determining a neutron spectrum unfortunately involves large uncertainties arising from the differentiation of the proton energy distribution and the variation of the effective shrinkage factor of the emulsion with dip angle ϕ for angles > 25 deg (*77*).

It has recently been found that the difficulties due to the necessity for measuring tracks with large dip angles can be eliminated in one of two ways. Dr. John Evans, while at Los Alamos, proposed and made some measurements with a method involving the exposure of two plates in planes 90 deg apart (*61*). In one of these plates, tracks are measured if ϕ is less than 45 deg, while in the second plate only those tracks that fall in the supplementary cone are measured.

An alternative method for avoiding the difficulties caused by the variation of effective shrinkage factor with dip is to process the plates in such a manner that they retain their original thickness. This can be accomplished by soaking the plates in a 10% aqueous solution of glycerine at 22° C and drying at approximately 50% relative humidity (*78*).* The plates must also be analyzed at the same relative humidity and temperature if changes in thickness are to be avoided. Variations in soaking time and glycerine concentration may be necessary for plates with different histories of exposure and development and for different temperatures and relative humidities. It is quite possible that a combination of the glycerine treatment with Evans' two-plate method would be superior to either by itself.

Other Methods

Two other methods for measurement of neutron spectra from extended, anisotropic sources involve the loading of the emulsion with Li^6 or B^{10}. The reactions, $Li^6(n,\alpha)H^3$ and $B^{10}(n,2\alpha)H^3$, are both exothermic.

Keepin and Roberts (*22, 38*) have done considerable work with Li^6. However, thus far the results are not too promising due, in part, to the fact that the cross sections with respect to angle and energy are mainly unknown for this reaction. Also there is a strong resonance at several hundred kilovolts where the method would be expected to have its greatest usefulness. At higher energies competition from n-p scattering makes the method difficult to use.

B^{10}-loaded emulsions (*15*) would appear to be useful at high energies. Since the energy is carried away by three particles, the direction as well as the energy of the incident neutron can be determined from the energies and directions of the alpha particles and triton. The difficulty here, however, is that the product of the cross section for the $B^{10}(n, 2\alpha)H^3$ reaction and the concentration of B^{10} that can be achieved in nuclear emulsions is very low compared to the product of the n-p scattering cross section and concentration of hydrogen in the emulsion.

NEUTRON SPECTRA FROM POINT SOURCES

When the source of neutrons is small compared to the source-detector separation, the methods available for making neutron spectrum measurements are much simpler to use and lend themselves to much higher precision than the methods already discussed.

External Radiator

When intensity is not an important consideration, the simplest method applicable to point sources, and the one that lends itself to the highest precision in the determination of the absolute number of neutrons emitted by the source as a function of neutron energy, is based on the use of the nuclear emulsion as a detector only (*39*). The radiator consists of a thin layer of polyethylene or paraffin containing either hydrogen or deuterium.

In this method the radiator and detector are placed inside a vacuum chamber in such a geometry that the axis of the radiator coincides with the neutron beam direction. The nuclear plate is oriented so that recoil nuclei from the radiator enter the emulsion surface at a suitable angle. The choice of entrance angle and emulsion thickness should, in general, be such that the particles are stopped within the emulsion volume; otherwise their energy cannot be determined.

For measuring purposes it is convenient to align the photographic plate so that the line from the center of the radiator to the center of the plate area analyzed passes through the neutron source and so that its projection on the plane of the plate coincides with the long plate axis.

As indicated above, the radiator usually consists of light paraffin, deutero-paraffin, light polyethylene, or deutero-polyethylene.* Deuterium compounds have the advantage that, at many neutron energies, the n-d elastic scattering cross section for scattering neutrons through 180 deg in the center-of-mass system is considerably greater than the corresponding n-p cross section. (At 14-Mev neutron energy, for example, the ratio of these cross sections is approximately 2.) On the other hand, there are the

* The range-energy relation for protons in C2 emulsion is now known to an accuracy of approximately 1% up to 14 Mev and with somewhat less precision up to 39 Mev.

* Hardening the emulsion in acid hypo inhibits the absorption of glycerine.

* The deutero-polyethylene was prepared for us by Dr. A. R. Ronzio of this laboratory.

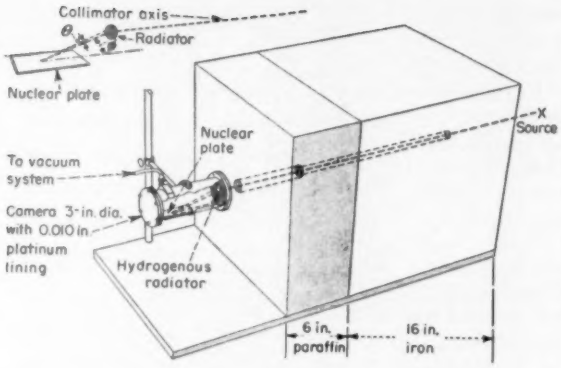

FIG. 3. Neutron collimator and camera. Radiator and detector are inside camera

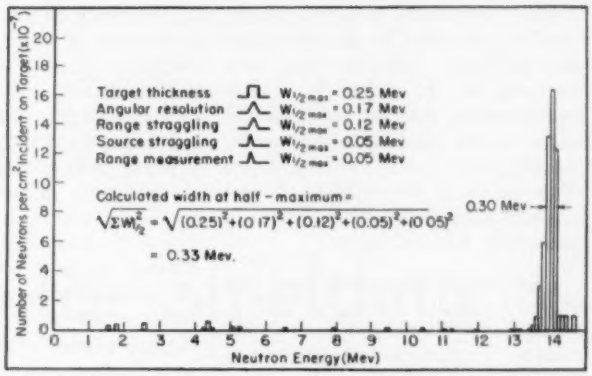
Number of Neutrons per cm² Incident on Target (x10⁻⁷)
Target thickness W1/2 max = 0.25 Mev
Angular resolution W1/2 max = 0.17 Mev
Range straggling W1/2 max = 0.12 Mev
Source straggling W1/2 max = 0.05 Mev
Range measurement W1/2 max = 0.05 Mev
Calculated width at half - maximum =
√ΣW1/2² = √(0.25)²+(0.17)²+(0.12)²+(0.05)²+(0.05)²
= 0.33 Mev.
0.30 Mev
Neutron Energy (Mev)

FIG. 4. Energy distribution of neutrons from T(d,n)He⁴ reaction; 200-kev deuterons

considerations that the range of a deuteron knocked on by a neutron is considerably less than the range of a proton knocked on by a neutron of the same energy—a disadvantage at low neutron energies—while at high neutron energies (~14 Mev) there is a not negligible cross section for deuteron breakup.

Collimation. In this arrangement, it is apparent that the nuclear plate records not only the trajectories of protons from the radiator but also the trajectories of proton recoils in the emulsion. (A 200μ emulsion irradiated by a flux in excess of 2×10^9 neutrons/cm^2 is unreadable.) It is therefore very often necessary, especially when thin radiators are being used, to shield the emulsions from the direct neutron beam to prevent the generation of an intolerable number of proton recoils.

To do this, we have successfully utilized a collimator made of iron backed by paraffin. Since iron has a large inelastic cross section for high-energy neutrons, the neutrons resulting from inelastic processes are emitted with relatively low energy and therefore have a high probability of being further degraded by the paraffin. Figure 3 displays the geometrical arrangement involving a collimator and a neutron camera, which contains a radiator and a detector.

Proton-recoil radiator. We shall confine the following discussion to the case of an H^1-containing radiator. If the radiator is small compared to the distance between the source and the detector, we have a "good geometry" experiment in which the neutron energies may be inferred from the proton recoil energies through the relation $E_n = E_p \sec^2 \bar{\psi}$, where $\bar{\psi}$ is the average angle between the neutron and proton directions, E_p is the proton energy, and E_n is the neutron energy.

The energy of a given proton is determined by applying the range-energy curve for dry emulsion to the proton range determined from the sum of the absolute range of the proton in the emulsion ($L = R_p \sec \psi$) and the emulsion equivalent of half the radiator thickness along the path of the proton. The plate analysis for this method is very straightforward and comparatively fast since it is necessary to scan only the emulsion surface. Once a track is found that starts on the surface and proceeds in such a direction as to be consistent with having originated in the radiator, the procedure is to measure the projected length of the track along an axis that coincides with the projection of the direction of the neutron beam on the emulsion surface (Fig. 3).

To formulate the procedure for obtaining the absolute number of neutrons as a function of neutron energy from the various measured quantities, it is convenient to define the following additional notation:

$F(E_n)$ = number of neutrons of energy E_n per cm^2 and per Mev incident on the radiator

A = detector area analyzed

$N(E_p)$ = number of protons per Mev, of energy E_p, projected from the radiator and incident on plate area A

Θ = solid angle in the laboratory coordinate system subtended by A at the radiator $= (A \sin \phi)/D^2$, where D is the distance between the center of the radiator and the center of the plate area analyzed

Ω = solid angle in the center-of-mass system subtended by A at the radiator

n_0 = number of hydrogen atoms, in the radiator, exposed to the neutron flux

$\sigma_{n-p}(E_n)$ = total neutron-proton scattering cross section (*79*) for neutrons of energy E_n

(All of the most recent differential scattering cross-section measurements on *n-p* scattering indicate isotropic scattering in the c. m. system up to 14 Mev. The error incurred due to an assumption of isotropy is certainly less than 3% even at 14 Mev.)

The neutron spectrum incident on the radiator may now be determined from

$$N(E_p)dE_p = F(E_n)dE_n n_0 \frac{\sigma_{n-p}(E_n)}{4\pi} \Omega \quad (2)$$

where

$$\Omega = (4 \cos \bar{\psi})\Theta \quad (3)$$

$$E_p = E_n \cos^2 \bar{\psi} \quad (4)$$

$$dE_p = dE_n \cos^2 \bar{\psi}. \quad (5)$$

To obtain the flux of neutrons per Mev at a given energy, E_n, we simply utilize the proton recoil energy distribution (corrected for radiator thickness) to evaluate $N(E_p)$ at $E_p = E_n \cos^2 \bar{\psi}$ and then solve Eq. 2 for $F(E_n)$.

In practice it is somewhat simpler to

tabulate the number of protons corresponding in range to predetermined neutron-energy intervals, i.e., one calculates for the endpoints of each neutron-energy interval the projected ranges in the emulsion of the corresponding recoil protons that originate at the center of the radiator. If one now multiplies the number of tracks in each energy interval by

$$\pi D^2/n_0\sigma_{n-p}(E_n)A \sin\phi \cos\Psi \quad (6)$$

one can immediately plot the absolute number of neutrons/cm², per energy interval, as a function of neutron energy. Only the quantity $\sigma_{n-p}(E_n)$ in the above factor varies with energy interval.

Figure 4 shows the time-integrated number of neutrons/cm² as a function of neutron energy at a point 1 meter from a neutron source produced by the bombardment of T, in a thick Zr-T target, by a molecular beam of singly ionized 200-kev deuterons.* The axis of the collimator (Fig. 3) was at right angles to the deuteron beam and the radiator was 2 mg/cm² polyethylene. It is seen that the width at half-maximum of the neutron distribution is well accounted for by the spread in energy introduced by target thickness, angular resolution, range straggling,† source straggling, and errors in range measurement.

The neutron flux at the detector, as calculated from counting a known fraction of the alpha particles from the subject reaction, agrees to within 5% with

$$\int_{13\ \text{Mev}}^{15\ \text{Mev}} F(E_n)dE_n \quad (7)$$

as determined from the neutron energy distribution plot (Fig. 4). The standard error due to statistical fluctuations amounted to ±3%.

Low-intensity flux. More often than not one is faced with the problem of determining the distribution in energy of a neutron flux of such intensity that a good geometry experiment such as the one just described is hardly feasible. It is possible to increase the proton track density on the plate by as much as a factor of 10 for a given radiator thickness by using a radiator that is not small compared to the separation of the radiator from the detector.

In such a geometry one must, however, use to the fullest extent the data derived from measurements on each track. A determination of the orientation of the track along with the coordinates in space at which it penetrates the emulsion suffices to determine the point on the radiator from which the ionizing particle originated and hence the direction between the incident neutron and the recoil proton. The energy of each recoil proton and the energy of the neutron that produced that recoil must now be determined separately. To determine the absolute number of neutrons as a function of neutron energy, one must evaluate the factor $(A \sin\phi \cos\Psi)/D^2$ (Eq. 6) by numerical integration.

PART TWO OF THIS ARTICLE

appearing in August, will conclude the discussion of point sources, and cover energy resolution and applications of the procedure

* Plates analyzed by Martha Downs, Margaret Gibson, and Opal Milligan.

† Range straggling arises from the discontinuous nature of the ionization process and the inhomogeneous distribution, in the gelatin, of the halide of the emulsion. At energies below approximately 3 Mev there is an important contribution to range straggling from the finite size and small number of grains comprising a track (*80*).

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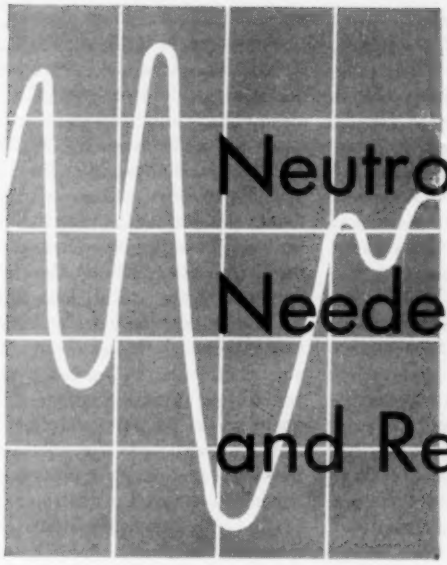

Neutron Data Needed for Shielding and Reactor Design

Interest in fast reactors, and work on the design of high-performance shields has shown that there is need for much investigation of neutron cross sections above 10 kev. This article tells what data is needed and why

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FROM THE START of interest in nuclear reactors, intensive effort has been put into developing methods for measuring low-energy neutron properties (*1*). As a result, it is today a relatively straightforward matter to obtain most of the desired cross sections below 100 ev.

There has been a growing need, however, for neutron data at higher energies, above 10 kev. The need has been fostered in part by the interest in fast reactors (such as EBR) and by the realization that the design of high-performance shields involves mainly neutron and gamma-ray properties in the Mev region. Our knowledge of many of these properties is still fragmentary, and the techniques for measuring them are not yet available.

It is convenient to treat shielding and reactor needs separately for the most part. The types of cross sections involved, the energies of interest, and the materials of importance are different in the two fields.

We will be concerned mainly with neutrons in the range from a few kev, about where the "fast choppers" leave off, to around 14 Mev. The region of interest has been interpreted, however, to include the measurements of energetic gamma rays resulting from slow-neutron reactions. No mention will be made of fissionable isotopes, but many of the remarks apply to them, too.

DATA OF INTEREST FOR SHIELDING PURPOSES

Shielding research at present is being conducted on three levels. The first level is completely empirical, centering about the testing of more or less full-scale mock-ups of almost fully designed shields. This is a necessary step in the construction of any present day, high-performance shield and is likely to be so for some time. Being completely concerned with actual shield tests, it has little need for microscopic data.

The second level might be described as phenomenological. Although still concerned with bulk shielding facilities, the experiments are of a more fundamental nature, with simpler geometries and compositions. Work at this level provides the important data for preliminary shield design. From the designer's point of view it is the most fruitful type of shielding research being conducted today.

There is great need for cross section data here. One seeks first to understand these bulk shielding experiments in a physical, semiquantitative manner in terms of known cross sections. The hope is that, with such understanding, there can be found a few phenomenological parameters, involving measurable cross sections, that adequately describe a material's bulk shielding performance. If successful, these parameters could then be determined for materials which, by reason of scarcity (or nonexistence in adequate amounts),

cannot be tested in bulk shielding facilities.

Although this entire procedure depends on a knowledge of microscopic data, no great resolution is required. The details of resonance structure, of angular distributions, or of inelastic spectra cannot be important. The bold outline of the picture is needed.

The third level is much more long range than the others. The aim here is the description of shielding behavior based on first principles, using nothing *but* microscopic cross section data. From the basic Boltzmann transport equation one seeks to derive the manner in which neutrons and gamma rays penetrate through matter. Admittedly, this approach is not yet of much practical importance. But considerable success has already been achieved in the special case of gamma-ray penetration, in the absence of neutrons (*2*, *3*). As a result, there is greater hope of solving the more general problem, and considerable work will be done on it in the next few years. At the least one can hope to put the phenomenological descriptions on a sounder, more understandable basis.

It is clear that this type of attack demands the most in the way of microscopic cross sections. Until enough experience has been gained to tell which features of neutron interactions are important and which can be disregarded, it will be necessary to describe the neutron processes as faithfully as possible. Only here is high-resolution nuclear data needed for shielding.

In the shielding of reactors, the basic source of fast neutrons is fission. The neutron spectrum has a maximum in around 1 Mev, and decreases rapidly thereafter, almost exponentially, falling by about $1/e$ every 1.5 Mev. In any practical neutron shield, however, the lower-energy neutrons are attenuated much more rapidly than those at high energies. Hence, the neutrons which penetrate large distances come from the high-energy tail of the spectrum; those which start out below 1 Mev quickly fall by the wayside.

The neutron energy range of interest, therefore, stretches from about 1 Mev to around 14 Mev, with the most important region for deep penetration being probably 4–8 Mev. This is an energy interval that is difficult of access with most current Van de Graaff generators. From the shielding point of view, therefore, it is important to develop sources for this region, even if they do not provide high resolution. Nereson's pioneering work in using analyzed continuous spectra (*4*) is promising, as are high-energy Van de Graaff generators and cyclotrons.

The materials of importance for shielding generally fall into three not mutually exclusive classes:

1. Light elements occurring in neutron shields, comprising most of the elements from $Z = 1$ to $Z = 9$.

2. Structural materials, principally Fe, but also Al, Co, Cu, Ni, Cr, possibly Ti, and Zr.

3. Heavy elements used for gamma-ray shielding, Pb, W, Bi, and U.

The list is not intended to be exhaustive, nor is it desired to exclude the long-range exploratory type of measurements. It does include almost all the elements employed now in significant amounts or proposed for use in the near future.

Inelastic cross sections are most important. Next in priority are angular distributions of scattered neutrons, then total cross sections, and, finally, reaction cross sections. Also of considerable importance are the energetic gamma rays produced in slow fission and neutron capture.

Inelastic Scattering

Inelastic scattering produces two effects. One is that the incident neutrons are degraded in energy and changed in direction. The other, of equal or greater significance for shielding, is that gamma rays are produced. If the inelastic scatterer is a heavy material, its effectiveness for gamma-ray shielding may be diminished in the presence of a fast-neutron flux if it is itself a source of photons.

The basic cross section for the neutron aspect may be written as $\sigma(E_0|E,\Omega)$, the differential cross section for scattering from E_0 to E with a scattering angle Ω. It will undoubtedly be quite some time before a complete picture of this cross section can be obtained for any isotope. Fortunately, it is not necessary; much simpler characteristics of inelastic cross sections will usually suffice. For example, it would be helpful merely to know the threshold energy at which inelastic scattering becomes significant (i.e., above a millibarn) in the middleweight and "magic" heavy isotopes. Besides giving some idea of the general importance of inelastic scattering in the particular element, this threshold marks the upper energy limit for collisions which do not absorb or degrade the neutron energy appreciably. Of primary concern here are structural materials such as Fe, Ni, etc., and the "magic" elements Pb and Bi.

The inelastic scattering measurements made so far indicate that, in the heavier elements (where inelastic scattering is most important), the scattered neutrons have quite low energies. They may be very quickly moderated and captured. In any event, they do not contribute appreciably to the penetration of fast neutrons. Consequently, on the second, phenomenological, level, inelastic scattering is treated as an absorption process merely serving to remove the neutron from the beam. (This approximation, in fact, has also been used in all the basic calculations to date.) With such a viewpoint, it is clear that only the total inelastic cross section matters.

$$\sigma_{in}(E_0) = \int \sigma(E_0|E,\Omega)\, dE\, d\Omega$$

Elements whose total inelastic cross sections are of interest are the heavy and medium isotopes, Pb, W, U, Fe, Zr, Ni, Cu, etc., and also some of the lighter ones, particularly O, N, C, and Al, in rough order of importance.

This is not to say that the energy spectra of the inelastically scattered neutrons are of no importance at all. As the phenomenological description grows in sophistication, it will undoubtedly include effects arising from the inelastically scattered neutrons.

For the basic calculations, the need for inelastic spectra is likely to come even sooner, although here the need will be chiefly for the light elements, particularly O, N, and C, at high energies. Since only a few levels usually participate in these elements, it would also be necessary to get some idea of the angular distributions of the inelastic neutrons. When many levels are involved, theory based on the continuum model of the nucleus predicts that the distribution is isotropic. This is probably the case, although the theoretical foundations are now under suspicion (*5*), and a few experimental checks would be reassuring.

The spectrum of gamma rays emitted is, for shielding, one of the most important characteristics of inelastic scattering for which information is needed. Of primary concern are the structural elements and heavy gamma-

ray shielding materials, particularly Fe, Pb, U, W, Ni, etc.

Until a short while ago, the only data on this subject had been obtained for the light elements, and mainly near the inelastic threshold. Very recently, Day (*6*) and Scherrer *et al.*, (*7*) (at 14 Mev) have obtained more useful information with scintillation spectrometers. It is to be hoped that these first investigations will lead to more thorough and detailed explorations of the spectra. The greatest urgency centers around the high-energy region for gamma rays of 2–4 Mev.

An attempted priority list for inelastic measurements of interest for shielding should, therefore, be: (1) total inelastic cross sections (including thresholds); (2) gamma-ray energy spectra; (3) neutron energy spectra; (4) neutron angular distributions; and (5) gamma-ray angular distributions.

Total Cross Sections

Two years ago the greatest need in microscopic data for shielding was for total cross sections. Thanks, however, to the work of the Wisconsin group (*8, 9*), and particularly that of Nereson (*4*) at Los Alamos, this need has been largely met, at least for the phenomenological level. There now exist, or will shortly, moderate-resolution measurements from 0 to 14 Mev for almost all elements of importance. The notable exceptions are B, Li, and W, which are unfortunate omissions since they are of great interest.

For the basic calculation needs, the situation is less satisfactory. Ideally, one would like to have fairly detailed knowledge of the resonance structure at higher energies, from about 3.5 Mev, the limit of present day (p, T) sources, to 14 Mev. The particular elements involved are again determined by the foreseeable nature of the fundamental calculations that may be carried through. Mainly, these concern O, C, N, B, and perhaps two or three of the heavier elements, Fe, Pb, and W, in rough order of importance.

Angular Distribution

The nature of information desired on the angular distribution of elastically scattered neutrons depends on the type of shielding activity considered. On the phenomenological level, it has proved useful in shielding theory to adopt a picture of scattering which assumes that any neutron elastically scattered beyond some angle is irrevocably lost to the beam and can be considered as absorbed. One is thus led to the concept of a cross section for removal from the beam which differs from the total cross section by the fraction of neutrons scattered within some vaguely defined near-forward direction.

The usefulness of this concept clearly depends on how well one can predict such an effective cross section on the basis of the microscopic data, meaning essentially the angular distribution. Knowledge of the transport cross section is of some help, but there is evidence that the $(1 - \cos\theta)$ factor is too broad a "rejection filter"; it excludes some neutrons scattered at large enough angles to be eliminated from the beam.

The older measurements of Aoki (*10, 11*) and recent ones by Jurney and Zabel (*12*) are in reasonable agreement with the predictions of the continuum theory. Recent theoretical work (*5*) casts some doubt about the validity of these predictions, however, and, for the present, they should be used with caution.

One would like to have some survey of the angular distributions, particularly above 1–2 Mev, to see to what an extent the older theory is satisfactory. The greatest controversy, moreover, centers around elements for which there has long been doubt about the applicability of the continuum theory, whether because they are too light or are "magic." For such cases there is need for measurements of the angular distribution up to 8 Mev averaged over relatively wide energy regions. This group includes all elements up to around $A = 20$, magic nuclei such as Pb, possibly Zr, and perhaps also Fe and W. Since the emphasis is on the forward peak, angular distribution measurements should be more finely spaced here, about every 20–30 deg.

As usual, the information desired for fundamental calculations is more detailed but perhaps less extensive. The need for angular distributions here is obvious; it furnishes the scattering kernel which must be "plugged into" the Boltzmann transport equation.

Where the resonance structure is sufficiently discrete and broad to be considered in detail in the calculations, it is necessary to know the angular distribution with high energy resolution. It is not likely that this can be done experimentally. However, measurements that are relatively widely spaced in energy often suffice to fix the level constants well enough so that the angular distribution can be reconstructed theoretically in as much detail as desired. The work of Baldinger *et al.* (*13*) has once and for all shown how powerful a tool the angular distribution is in fixing level parameters.

Such detailed information is desired for most of the light elements, particularly D, B, Be, Li, O, C, N, and, if possible, also for Pb. For the lighter elements, such as C and O, some of the measurements exist in large measure up to ~3 Mev; the need is to extend them to higher energies.

To mention a specific problem, calculations now in progress on neutron penetration in water urgently require information on how the angular distribution in oxygen differs from the predictions of the continuum theory in the region 4–14 Mev. Even low-resolution data would be highly useful.

Gamma-Ray Spectra

The sources of gamma rays of interest for shielding are quite diversified—prompt gamma rays emitted in fission, fission-product gamma rays, neutron-capture gamma rays, and finally those from inelastic scattering. Of the elements of interest, only the capture gamma-ray spectra of H, Na, Ti, Pb, and Bi have been surveyed accurately enough to be of use (*14–16*). Except for this handful of data, *the absolute energy spectrum is not adequately known for any of these sources.*

Consider, for example, the prompt fission gamma rays. All investigations (*17–19*) on this subject agree that the total energy emitted is around 5 Mev per fission. Deutsch and Rotblat (*17*) indicate that the average photon energy is 1 Mev, whereas Kinsey *et al.* (*18*) have reported a figure of 2.5 Mev. Recent experiments of Rose and Wilson (*19*) tend to agree with the 1-Mev value, but give indications of the presence of a harder component in addition. The difference between 1 and 2.5 Mev is obviously of importance in considering how these gammas penetrate matter.

Admittedly, the experiments are not easy; it is quite difficult to separate the prompt fission gamma rays from those produced in the fissionable isotope, or emitted by short-lived fission products. From many points of view it is, of

course, desirable to be able to separate these three sources. It should be emphasized, however, that the distinction is of little importance for shielding of thermal or intermediate reactors. What is wanted is the total prompt or near-prompt gamma-ray spectrum produced by neutron absorption, whether such absorption results in fission or simple capture. The investigation by Motz (*20*) of the spectrum from a uranium slug in the Los Alamos water boiler, and some experiments understood to be in progress at ORNL on the swimming pool reactor (*21*) come closest to providing the needed data.

A good deal of work has gone into the examination of capture gamma spectra. Kinsey and his collaborators (*14–16*) have been especially diligent in measuring the high-energy regions of the spectra for most of the lighter-weight elements. However, the particular information desired for shielding has only rarely been obtained. There is little interest in the spectrum below about 1 Mev (and certainly none in the discrete line structure in this region) since one can easily and economically absorb this portion of the spectrum. The important region centers around 3 Mev, stretching from 1 to 6 Mev.

Although no great resolution is required, it is vital that the spectrum be obtained in absolute measure, as the number of photons per capture per unit energy range. Few of the experimental techniques employed so far can provide this type of information in the energy region of interest, and the amount of usable data is meager. It is to be hoped that the recent experiments of Braid (*22*) and Motz (*23*) on the spectra below 3 Mev are harbingers of extensive future work in this region.

Fast-Neutron Reactions

It is only in the light elements that fast-neutron reactions can be of sufficient importance to constitute a substantial absorptive process. Examples are the well known (n,α) reactions in Li, B, N, and O and the (n,p) reactions in N and O. Practically none of these have been measured adequately above 2–3 Mev, and the need for excitation function measurements here is obvious.

Sometimes the reactions are not of direct shielding importance, but result in activations of the shield material or coolants which may be annoying sources of radiation. The O^{16} and $O^{17}(n,p)$ reactions are examples. The

Possible Threshold Reactions

Reaction	*Threshold (Mev)*
$S^{32}(n,p)$	1
$Co^{65}(n,p)$	1.5
$Te^{45}(n,p)$	2.2
$Sn^{116}(n,p)$	2.4
$Fe^{56}(n,p)$	2.9
$Ba^{138}(n,p)$	3.1
$Rb^{87}(n,p)$	3.2
$Mg^{24}(n,p)$	4.7
$Ta^{181}(n,2n)$	7.4

$O^{16}(n,p)$ excitation function has been measured adequately from 12 to 18 Mev at Los Alamos (*24*).

One of the greatest problems confronting fundamental experiments on the passage of neutrons through shields is the lack of a suitable means of measuring uncollimated fast-neutron spectra. Development of various scintillation devices and of the $He^3(n,p)T$ counter gives hope that this obstacle will be overcome shortly. Until this is accomplished, there is some interest in cruder methods to obtain information about the neutron spectrum, such as threshold detectors using (n,p), (n,α), and perhaps $(n,2n)$ reactions.

Two types of developments are needed to be able to use threshold reactions for measuring feeble fast-neutron fluxes. One is the establishment of quantitative chemical processes for concentrating the activated isotope. The other is the measurement of the yield curve. Some of the possible reactions that seem most suitable from the standpoint of cross section and threshold are listed in the table.

Only for the $S^{32}(n,p)$ reaction has there been measurement of the excitation function (*25*), and this is so difficult to explain theoretically that a remeasurement seems desirable. These measurements would also permit a check of the continuum theory of neutron reactions (*26*).

DATA OF INTEREST FOR REACTOR DESIGN

In considering the unclassified fast-neutron cross sections of interest for reactors, a number of differences from the shielding situation must be noted. For example, not much effort in reactor theory is being devoted to what corresponds to the basic level in shielding calculations. Although this situation may be expected to change in the future, it is still true that there is little need in reactor work for high-resolution data; rough energy averages will be adequate.

One must also be careful to distinguish between the types of reactors. A process that may be advantageous for thermal reactors (e.g., inelastic moderation) may be a difficulty to be avoided like the plague in fast reactors.

Compared to shielding, the energy range of interest for reactors is considerably reduced. For practical purposes there is little interest above 4 Mev since there are few neutrons above this energy in the fission spectrum. Even 2 Mev is a satisfactory limit.

The elements of importance are more widely spread over the periodic table than they are in shielding. Roughly they may be categorized as moderators (necessarily light), reflectors, structural materials (as in shielding), and coolants (including Li, H_2O, Na, K, and Hg). In addition there will be interest in elements used in control mechanisms, as constituents of fuels (N in UNO_3), and appearing as products of neutron reactions.

Generally speaking, the three types of fast-neutron data (unclassified) involved in reactor design are (1) inelastic scattering; (2) angular distribution of elastically scattered neutrons; and (3) energy variation of fast reaction cross sections.

Inelastic Scattering

Reactivity calculations obviously involve only neutrons; in contradistinction to shielding there is no interest in the gamma rays produced in inelastic scattering. The total cross section is of some help, but of most interest is the energy distribution of the inelastically scattered neutrons.

The energy regions of importance vary with the type of reactor. In thermal reactors, for example, inelastic scattering is an aid in moderating the neutrons. The spectrum of the relatively fast neutrons is in large measure determined by this process. The neutrons which reach low energy solely by inelastic scattering are few compared to the bulk of neutrons which have been moderated by elastic collisions. Hence, the energy spectrum down to around 500 kev is adequate, with some information as to how many are scattered to below this energy.

In fast reactors, inelastic scattering is often the only means by which unwanted energy degradation can occur. Neutrons can reach low energies, where absorption cross sections are high, only by the inelastic route. For this reason, there is some interest for fast reactors in more detailed inelastic energy spectra, particularly in the low-kev region. It is realized that such low-energy spectra will be extremely difficult to measure, but here perhaps is a case for which the time-of-flight method is uniquely adapted.

Among the elements which may be considered most important are the fissionable fuel isotopes and the structural materials, especially Fe. These are inevitable in any reactor. Coolant and reflector are often so light that inelastic scattering is not significant, but in some coolants, such as Hg or Pb, it cannot be neglected.

Angular Distributions

Someday, perhaps soon, reactor calculations may reach the stage where detailed knowledge of the angular distribution of scattered neutrons is required. For the present, and for most calculations, it seems adequate to assume that neutrons are inelastically scattered isotropically. In the significant regions of energy degradation it usually can be assumed that elastic scattering from a moderating element is nearly isotropic (in the center of mass system).

First-order corrections for deviations from isotropy are usually in terms of the *transport cross section*, and it is as this quantity that information on the angular distribution is most urgently needed. The usual moderators above H, i.e., D, Be, C, and O, probably come first in order of importance. Next are structural elements, particularly Fe, then coolants and reflectors.

It should be noted that since the energy, and also often the atomic weight, is often lower than for shielding interests, the theoretical predictions of the continuum theory are less frequently applicable here and recourse must be had to experiment.

Reaction Cross Sections

Fast-neutron reaction cross sections are only of importance in the fast reactors, particularly so in breeders. Here one is trying to stretch the neutron economy as much as possible to get high breeding gain. Hence, absorption cross sections, even in the millibarn region, may be of importance in substances that occur in large quantities in the reactor.

The work of Hughes (*27*) and his collaborators has been invaluable in mapping out the variation of fast-neutron (n,γ) cross sections as functions of neutron and proton number. By and large it is now possible to predict the (n,γ) cross section, for fission neutrons, to within a factor of 2–4 for any given isotope.

The results so obtained pretty well delimit the elements that can be allowed in a fast breeder in appreciable quantities. Only the light elements below Zn (but not so light as to cause moderation) and those in the vicinity of the magic isotopes can be used. There is still some difficulty with regard to isotopes on the sides of the magic-number "ditches." Here fluctuations from one isotope to another are large, and one cannot use the curve for interpolation; isotopes must be measured individually. Some isotopes below Na also require measurement.

Another question is the energy dependence of the cross section. For various reasons—effects of higher angular momenta, presence of competing processes—the usually quoted (*27*) $1/E$ dependence is not a safe guide.

The situation is perhaps not so fortunate with respect to other types of fast-neutron absorption processes which may act as poisons in fast reactors. The cross sections here depend upon threshold as much as upon the more smoothly varying statistical properties of the nucleus, and these thresholds are often unknown.

Some (n,p) and (n,α) cross sections for fission neutrons have been measured by Hughes (*27*), but, unfortunately, too few to answer all questions. Further, because of barrier effects, the variation with energy becomes more important than for the simpler (n,γ) reaction. All measurements so far have really been of activation cross sections. Some important reactions do not result in significant activation, and serious errors have resulted from assuming the equivalence of activation and absorption cross sections. It would be extremely worthwhile if some thought could be given to the difficult problem of measuring a reaction cross section in the absence of activation.

It is difficult to give a list of the elements for which fast reaction cross sections are needed—it varies greatly according to the specific design of the reactor. Structural materials are usually common factors, including Fe, Ni, Cr, Cu, Zr, Mn, and Zn, in rough order of importance. Beyond these, the coolant is probably the next largest source, such as Na and K.

One fast reaction, $Be^9(n,2n)$, deserves notice for a number of reasons. First, it is not an absorption reaction but helps produce fast neutrons. Second, it is of interest from a basic nuclear physics point of view. Third, the cross sections reported (*28, 29*) for it vary over a huge range, from millibarns to the impossibly large value of 4 barns.

* * *

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Radioisotope Procedures with Laboratory Animals

With increasing use of radioisotopes in the small-animal laboratory, adequate management and experimental procedures are needed. Considered here are general management, isotope administration, and balance studies after administration

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IN RADIOISOTOPE INVESTIGATIONS with small animals, it is imperative that special consideration be given to:

1. Sanitation and good housekeeping practices.
2. Availability of essential equipment and facilities for handling and monitoring employed levels of radioisotopes (*1–4*).
3. The perfection of techniques for the quantitative administration of activity to the animal.
4. Provision of facilities for animal restriction and maintainance, and for separate quantitative collection of excreta.
5. Controlled area segregation of the experimental animal cages and equipment following administration of radioactivity.
6. Satisfactory disposal of all excreta, carcasses and the radioactive wastes.

General Management of Animals

Management of animals, until such time as they are treated with radioisotopes, is no different from that in any conventional colony (*5–9*). It has been found convenient and satisfactory to maintain rats and mice in racks of conventional cages, and rabbits or guinea pigs in commercial units.

When tracer levels of an isotope are to be given, the animal is removed from the colony cage. After treatment, it is placed in isolated commercial cages or adapted metabolism units with feces-urine separators. If high levels of activity are involved, the animals may be placed in metabolism cages or holding units designed for immediate discard at the termination of the experiment.

A comprehensive report presenting the qualitative specifications for the design and construction of animal laboratories for radioisotope work has been compiled by Little (*10*).

It is important that separate rooms, or a portion of the animal room in smaller laboratories, be set aside for the radioisotope studies. Instruments, cages, and equipment for each isotope involved should be maintained separately and properly labeled on the basis of periodic measurements of residual activity. When multimillicurie levels are employed, as in LD-50 studies, then additional precautions including proper shielding or barricades must be provided to isolate the area for the protection of the participating personnel.

Isotope Administration

The radioactive material is made ready for administration to the animal in accordance with the usual "hot" laboratory procedures (*11*). Barricades, localized vessel shielding, and remote-control devices are utilized to minimize radiation hazards (*12, 13*).

The problems unique to biological experimentation arise in the administration of radioactive material and in the care and handling of the animals after dosing. In this laboratory, it has been found most convenient to use a predesignated table centrally located and properly protected with diaper paper as a place for administration of all isotopes. Necessary instruments are kept in labeled individual porcelain or Pyrex trays. Clean and marked metabolism units for each isotope prevent cross contamination.

Delivery of radioactive materials, particularly to large numbers of animals, presents the problem of avoiding total body exposure and especially intense localized exposure to the hands of personnel. This may be minimized by: (1) using only that amount of activity necessary to accomplish the experimental objective, (2) providing for maximum distance between activity and the personnel administering the dose, (3) keeping personnel exposure time to a minimum by organization of procedures, and (4) using shielded syringes, especially when gamma emitters are being studied (*3*). Repeated "dry runs" assist in avoiding many of the difficulties in these methods.

Oral. With small animals, oral administration of activity in solution is usually the most practical and is accomplished most easily by stomach tube. Small commercial catheters, short pieces of polyethylene tubing attached to the end of a fitted needle, or a ball-pointed metal stomach tube*

*Available from Phipps and Bird.

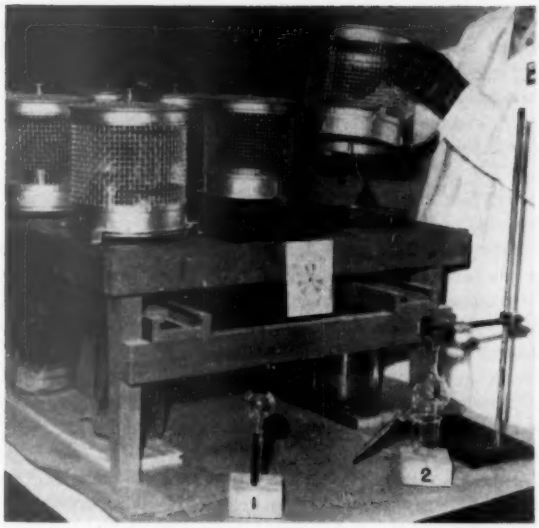

FIG 1. Cage-arrangement metabolism units using two methods, described in text, for separate collection of feces and urine

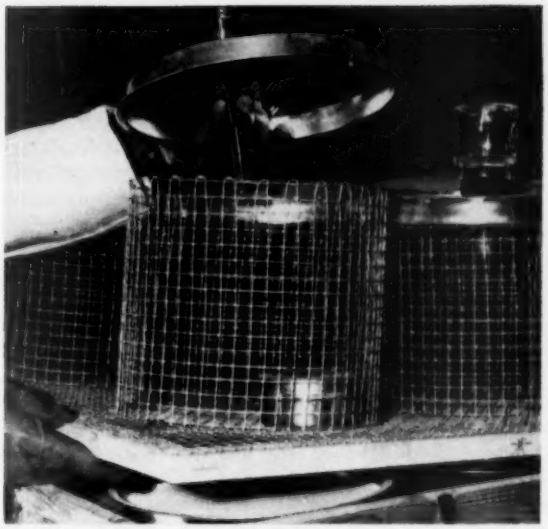

FIG. 2. Holding cage for use when balance studies are not required. Parts are inexpensive and can be discarded

that attaches directly to the syringe may be used for rats, rabbits, mice, or guinea pigs.

With mice or weanling rats, the metal stomach tube or the polyethylene catheter has been found most satisfactory in this laboratory. With dogs or small pigs, the conventional rubber stomach tube used for man has proved satisfactory when an insert of small-diameter polyethylene tubing is clamped within it to reduce surface area and loss due to adsorption during administration (*3*, *4*).

The following procedure is used for oral administration to rats, mice or guinea pigs:

1. The animal is immobilized without anesthesia by grasping the head and shoulders firmly with the left hand, or by wrapping in a small towel.
2. The mouth is opened by slight positive and upward pressure over the jaws by the thumb and forefinger.
3. The stomach tube assembly is carefully inserted with the right hand.
4. The syringe containing the activity is brought up by an assistant and injected directly into the delivery tube.
5. The dose is washed quantitatively into the animal's stomach.
6. The animal is placed in the metabolism unit.

A standard solution is usually prepared at this time by repeating the procedure with delivery of the dose into a volumetric flask. This assembly and method permit orientation and rechecking of the instruments and procedure before each administration to the animal.

In toxicity studies, or where several hundred animals are involved, a simple and safe method employed by Shay and Gruenstein (*14*) for the gastric instillation of fluid may be used as a time-saving device. The apparatus designed by Talalay and Takano (*15*) for tube-feeding rats may likewise be employed to incorporate the activity into the feed for daily administration. Both of these procedures, however, involve a sacrifice of accuracy for speed and convenience.

Intraperitoneal, subcutaneous or intramuscular. With small animals, these procedures offer no major difficulty. The animal and the site of injection are prepared in the usual manner (*16*).

The rat, mouse, or guinea pig is immobilized by holding with the left hand, or by wrapping in a towel, while special holding devices are used for rabbits or dogs. Anesthesia is usually unnecessary. The needle is inserted and the radioactive solution administered directly as previously discussed for quantitative oral administration. For extremely high-level studies with gamma emitters, a shielded syringe (*3*) or the semiautomatic injection apparatus designed by Holt (*17*) for remote-control injections may be used.

Intravenous. The most difficult procedure with small laboratory animals is perhaps that of quantitative intravenous administration. Complete immobilization is mandatory and usually necessitates complete anesthesia.

Because of the thin wall of the vein, leakage is difficult to prevent even when the use of a catheter is feasible. With rabbits (*18*), dogs (*19*), or small pigs (*3*), the problem is not critical because of the ease of complete immobilization without anesthesia, ready access to the ear, jugular, or femoral vein, and the size of the vein which allows for catheterization. However, with rats, mice, or guinea pigs, considerable practice is usually required for an individual to accomplish intravenous injections satisfactorily. One of the lateral tail veins may be used in anesthetized mice or rats following preinjection dilation of the vessels by bathing the tail in warm water or by a light application of xylol to the area. Finkel *et al.* (*20*), using mice, pointed out that engorgement of the vessels produced by a bath at 46° C for 5 sec facilitates the injection of solution into the tail vein. Others (*16*) have used the external jugular vein with apparent success, but, for the smaller animals of all ages and sizes, the femoral vein appears to be a most satisfactory route.

In practice, the anesthetized animal is secured to the operating board on its back, leaving the inside of the rear leg accessible. The hair is removed and the area thoroughly cleaned. The femoral vein is disclosed by light pres-

sure, a parallel 1–2 cm incision is made in the skin with a sharp scalpel, the fascia pulled back by blunt dissection, and the vein exposed.

A short 27-gage olive-pointed needle, attached to a tuberculin wash syringe by a short length of gum-rubber tubing, is then carefully inserted through the fascia and outer surface of the muscle slightly to the left and parallel to the vein. Dilating the vein by pressing the leg above the slit to cause vessel engorgement assists the operation. The needle is inserted into the side of the vein and is tested immediately by removing the pressure and drawing blood. The syringe, containing the activity, is brought up and injected directly into the attached rubber tubing and washed quantitatively into the vein with a small volume of normal saline from the wash syringe.

After a few seconds, the needle is removed and the injection area pressed slightly with a cotton applicator for closure. If the skin is shifted to one side before the slit exposing the vein is made, it will not be directly over the vein when released and suturing will not usually be necessary. After dosing, the incision is sutured if needed, covered with collodion, and the animal is placed directly in the metabolism cage.

Various modifications of this technique have been reported. Osserman and Mack (*21*) described a simple apparatus for multiple uniform intravenous injections of fluid, and Rhodes *et al.*, (*19*) developed a technique for continuous intravenous administration of nutritive solutions to dogs, which might be suitable for radioisotope procedures. A satisfactory apparatus for prolonged and repeated intravenous infusion in rabbits has been described by Detrick and Rhodes (*22*), and Nickson and Barkulis (*23*) have presented a holding apparatus to facilitate mouse tail vein injections.

Intratracheal and inhalation. In consideration of health hazards to personnel and the need for information on relative toxicities of insoluble dust suspensions and certain volatile compounds and gases, procedures for these routes of administration have been developed.

The tracheal route permits known amounts of toxic materials to be introduced directly into the lungs and allows a more rapid appraisal of pulmonary toxicity and absorption from the lungs than is possible by the more difficult inhalation studies. This technique has been employed effectively for beryllium by LaBelle and Cucci (*24*). In practice, the trachea is exposed and the needle is inserted between the rings for injection of the solution into the lumen as previously described.

An inhalation chamber has been designed by Baurmash *et al.* (*25*) for studying the effects of air-borne contaminants. A rotating platform in a circular chamber permits uniform exposure of a number of experimental animals. The apparatus is easily cleaned and decontaminated. A mist chamber, described by Sprague *et al.* (*26*), has been employed in inhalation toxicity studies with beryllium sulfate. Smith and Gardner (*27*) described an exposure chamber for hydrogen fluoride inhalation by rabbits, and LaBelle *et al.* (*28*) constructed a complicated apparatus, fitted with a system of electronic controls, for study of uranium dioxide dust inhalation by rabbits.

Management After Dosage

After administration of radioactivity, the animal must be considered as a source of external radiation and as an origin of contaminating excreted and expired radiomaterials. Only after use of relatively large amounts of activity is there a significant hazard to personnel from external radiation. However, the possibility of effects of one animal on another should be taken into consideration where they are housed close together over prolonged periods of time. The difficulties from excretions depend again upon the levels used, but more particularly upon the physical and metabolic characteristics of the radioactive element or compound employed.

When it is necessary to make quantitative separate collection of urine and feces, the cages and separators should be designed so that: (1) with a minimum of surface area exposed to the excretions, evaporation losses are reduced, (2) they can be easily cleaned of accumulated radioactivity, (3) cross contamination of feces and urine is minimized, and (4) they may be readily replaced and discarded when contaminated.

Rats, mice, and guinea pigs. Numerous methods have been used with rats and mice for the separate collection of excreta (*29–39*).

In this laboratory, the equipment described by Hansard *et al.* (*4*), and illustrated in Fig. 1, satisfactorily meets the requirements. The conventional mesh-wire metabolism cages have removable and disposable bottoms and are supported over a 10-in. glass funnel by a fitted wooden rack. A small inverted funnel, suspended by a wire from the center of the mesh bottom of the cage, directs the urine and feces to the sides of the large supporting funnel and minimizes splattering. The neck of the supporting funnel is cut off at the base to allow a 1–2 cm opening that fits over the separators beneath.

Two units that have been found satisfactory in this laboratory are illustrated in Fig. 1. The separator designated as No. 2 (*32*) has certain advantages when adult animals are used, or where several animals per cage are being processed, but is fragile and more expensive. For individual balance studies, where periodic samples are to be taken, the No. 1 unit more nearly meets the requirements (*4*).

The latter unit consists of a 1–3 cm glass bulb blown from a 5-in. length of 30-mm glass tubing and drawn to a closed point 8–12 cm from the top; a 15–30 ml graduated centrifuge tube restricted on 4 sides to fit the neck of the bulb, leaving space for the urine to flow around the bulb and down the sides into the tube; a 3 × 3-in. block of wood with a center hole drilled to fit the tubes; and a 2,000-ml Pyrex beaker. The unit is assembled by first placing the bulb in the tube. The tube is fitted in the prepared block support which is placed in the large beaker. The bulb is centered about 3–5 mm beneath the funnel supporting the cage, and the unit is ready for operation. The urine passes around the bulb into the tube, and the feces, on striking the bulb, bounce into the large beaker. This arrangement can be readily used with conventional metabolism cages.

In studies where quantitative separate collection of urine and feces is not necessary or when LD-50 studies are involved, the inexpensive racks and cages illustrated in Fig. 2 have been found highly satisfactory. The frame, the supporting ½-in. hardware cloth, and the cages themselves may be discarded when contaminated.

The cages are constructed from a single length of 12 × ¼ in. hardware cloth, and a 10-in. cake pan serves as a cover. A hole in the top of the cover

pan permits insertion of an 8-in. glass tube attached to the water bottle for convenient watering and refilling. The feed, in the form of pellets, may be placed directly upon the floor of the cage or placed in containers during the experimental period. Feces and urine pass through the wire mesh for collection on a tray or on excelsior. These are discarded periodically or at the termination of the study. This procedure minimizes personnel exposure time, adequately restricts the animal, and minimizes area contamination following isotope administration.

Rabbits. In studies with rabbits involving collection of excreta, consideration must be given to the problem of coprophagy. When "recycling" of ingested fecal material interferes with the experiment, the animals should be collared (*40*).

Selected commercial metabolism cages, preferably with removable bottoms, have been satisfactorily adapted for use in radioisotope balance studies with rabbits. When it is desired to use several animals per lot, the commercial dog cage has been found satisfactory. The wire-mesh bottoms should be made from ½-in. hardware cloth or equivalent and the removable metal tray sprayed with strippable paint* to facilitate rapid movement of excreted urine and ease of cleaning.

It is important that the feces pass readily through the wire floor to prevent recycling of nutrients or animal contamination. A round piece of ¼-in. hardware cloth, 6–8 in. diameter with a raised center, placed over the urine outlet in the metal tray serves to hold the feces away from the neck of the funnel and minimizes cross contamination of the urine with feces. In experiments with calcium-45, where the greater part of the activity is in the feces, the low level of activity found in the urine confirms the adequacy of the procedure.

In operation, the urine carboy first is removed and the feces collected before the trays are washed down for salvaging of any adhering activity.

Dogs. Gies (*41*) and Bliss (*42*) have described conventional metabolism units for dogs whereby the feces are retained by a wire floor and the urine is passed through the mesh and directed by a metal funnel to a collecting vessel beneath the floor. In radioisotope studies, however, contamination of the area and the animal itself with excreta must be minimized.

Hansard (*43*) has described a circular cage which effects the satisfactory quantitative separate collection of urine and feces eliminated by either male or females and avoids the fecal contamination which may occur in conventional units. A circular false floor comfortably supports the animal above a wire-mesh collection unit during the experimental period and keeps the animal oriented in such a way that all feces, regardless of the animal's position in the unit, pass through the circular openings and are collected below on the removable mesh floor. The urine passes through the mesh onto a galvanized metal funnel which diverts it into a carboy below.

Collection of expired gases. Special precautions must necessarily be taken in experiments where the activity may be present in a gas or expired air. This is particularly the case with isotopes such as carbon-14 (*44, 45*), tritium (*46*), and radon (*47*).

Carbon-14 is of tremendous value in metabolism studies. In general, a high percentage of carbon-14 administered to an animal is rapidly eliminated as CO_2 (*45, 48*). Tritium may also become widely used to label a large variety of physiologically important compounds. This isotope may be a considerable health hazard; it undergoes wide distribution in the animal's body, and indications are that some may be tightly bound in the tissues.

Even where the levels are so low that no health hazards exist, there may still be the possibility of cross-contamination of animals housed close together.

If it is only necessary to dispose of expired gases, various arrangements may be employed utilizing hoods or other means of effective ventilation. Specialized cages may be used to trap the expired gas quantitatively for subsequent measurement and are practical for use with small laboratory animals. A metabolism mask with a plastic face piece for dogs has been described by Gaeher (*49*) that may be suitable for radioisotope studies involving gas exchange.

* * *

This article is published with the approval of the director of the Tennessee Agricultural Experiment Station.

* A strippable paint called "Cocoon" available from Hollingshead Corporation, Camden, New Jersey.

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Distribution of Radioactivity in Labeled Polymers

Radioisotope distribution in a polymer depends on the labeling method used. Methods discussed are preparation from labeled monomers, addition of active groups to unreacted linkages, and mixing labeled and unlabeled polymers

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THE RADIOACTIVITY LEVEL of a sample is ordinarily assumed to be directly proportional to the quantity of material involved. If applied to tagged polymers, this principle carries with it the assumption that the polymer weight and radioactivity distribution functions, in terms of molecular size or chain length, coincide. However, this is true only under special conditions.

Distribution of radioactivity in the polymer depends on the labeling method used. To examine the variations in distribution, it is helpful to employ the mathematical formalism developed by Flory (*1*) for linear condensation and addition polymers. For simplicity, attention is restricted to polymers which have not been fractionated.

Polymerized Labeled Monomer

If N_0 molecules of monomer having r units of radioactivity emanating from some labeled atom are polymerized, the total radioactivity is

$$R_t = N_0 r \qquad (1)$$

For each X-mer species in the radiopolymer, the radioactivity per molecule is $x \cdot r$; so for N_X molecules of this species, the net activity then becomes

$$R_X = N_X \cdot x \cdot r \qquad (2)$$

In the case of a linear condensation or addition polymer, the relation for N_X is

$$N_X = N_0 \frac{(1-p)^2}{p} p^x \qquad (3)$$

where p represents the degree of polymerization with values $0 \leq p \leq 1$. Hence for the radioactivity distribution in the polymer, combining Eqs. 2, 3 and 1

$$R_X = R_t \frac{(1-p)^2}{p} x p^x \qquad (4)$$

The weight distribution for the polymer, similar to Eq. 4, is

$$W_X = W_0 \frac{(1-p)^2}{p} x p^x \qquad (5)$$

where W_0 is evidently the total weight of sample. Thus it is apparent that the specific activity R_X/W_X for each X-mer is the same as that for the total polymer, i.e.

$$\overline{R_X} = R_X/W_X = R_t/W_0 \qquad (6)$$

In the preceding analysis, all monomer units were radioactive; complication may arise if only a fraction is labeled. However, under conditions of ideally random condensation or addition with a reasonable quantity of radioactive monomer present, it is likely that a constant fraction of the polymer X-mers are labeled. If this fraction is α, the total radioactivity of the "diluted" monomer is

$$R_t = \alpha \cdot N_0 \cdot r \qquad (7)$$

Now for each X-mer species, on the premise of a fixed portion of the polymer molecule being labeled

$$R_X = N_X \cdot \alpha \cdot x \cdot r \qquad (8)$$

Introduction of Eq. 3 gives

$$R_X = N_0 \cdot \frac{(1-p)^2}{p} \cdot \alpha \cdot r \cdot x p^x \qquad (9)$$

which, from Eq. 7, is clearly seen to be identical with Eq. 4. Accordingly, the polymer prepared from diluted monomer may be expected to exhibit the same constancy of specific activity as prescribed by Eq. 6.

Addition to Unreacted Linkages

It is often more convenient to label a polymer after polymerization has

been carried out. Thus, for example, in the physiological and clinical studies involving PVP and certain natural proteins, radioiodine has been employed as a radioindicator.

An addition polymer will serve to illustrate the essential features of a polymer labeled at its residual linkages. Presumably the fate of the terminal double bonds in such polymers is not a definitely settled matter. Indeed, there is much that remains to be done in the way of illuminating the mechanisms of polymerization (*2*). In view of the uncertainty, it will be assumed that the terminal linkages are unsaturated. This approach will yield conclusions which can then be experimentally verified by alternative methods of labeling.

In any system of end-group analysis, the distribution of the number of end-groups is identical with the number-distribution relation stated in Eq. 3. Hence, for the total number of unreacted terminal linkages of an addition polymer

$$N_t = N_0 \cdot \frac{(1-p)^2}{p} \sum_{x=1}^{\infty} p^x \quad (10)$$

so that

$$N_t = N_0(1-p) \quad (11)$$

If now the relative uptake of a radioisotope, say I^{131}, is established in terms of the ratio W_I/W_0, where W_I and W_0 are the respective quantities of iodine and polymer, then from simple stoichiometry

$$W_I = 2 \cdot (N_t/N) \cdot M_I \quad (12)$$

N being the Avogadro number and M_I the atomic mass of iodine. Thus

$$W_I/W_0 = 2 \cdot (M_I/M_0) \cdot (1-p) \quad (13)$$

with M_0 the monomer molecular weight.

The distribution of radioactivity in the polymer so labeled is

$$R_X = R_t \cdot N_X/N_t \quad (14)$$

which, with Eqs. 3 and 11, gives

$$R_X = R_t \cdot \frac{(1-p)}{p} \cdot p^x \quad (15)$$

The fact that Eq. 15 is no longer of the same form as Eq. 4 gives rise to asymmetry of specific activity.

Thus, for the X-mer weight in the iodinated polymer,

$$W_{X,t} = W_X + W_I \cdot N_X/N_t \quad (16)$$

which, from foregoing considerations, gives

$$W_{X,t} = W_0 \cdot \frac{(1-p)^2}{p} \cdot xp^x + 2W_0 \cdot \frac{M_I}{M_0} \cdot \frac{(1-p)^2}{p} \cdot p^x = W_0 \cdot \frac{(1-p)^2}{p} p^x \cdot (x + 2 \cdot M_I/M_0) \quad (17)$$

The ratio of Eqs. 15 to 17 gives for the specific activity distribution

$$\bar{R}_X = (R_t/W_0)(1-p)^{-1} \cdot (x + 2M_I/M_0)^{-1} \quad (18)$$

which indicates a disparity between high and low molecular weight fractions that is augmented sharply as $p \to 1$. At large enough values of x, the specific activity of each X-mer falls off linearly with $1/x$.

Mixing with Unlabeled Polymer

Situations may arise when, for example, it is desirable to reduce the net specific activity, or to label a greater quantity of material by adding a comparatively smaller amount of tracer polymer. If the nonradioactive polymer is completely identical with the polymer formed from tagged monomer, then no alteration in the distribution of radioactivity or specific activity will be expected. However, it is extremely unlikely that this will be the case since the distribution functions are very sensitive to slight changes in the purity of monomer, conditions of polymerization, etc. (*3*); distinct batches of polymer are not likely to have identical p values. Thus it will be the usual circumstance to anticipate activity modifications in the diluted specimen.

Let us suppose that W_0 grams of unlabeled polymer, polymerized to p_0, are mixed with W_L grams of labeled polymer with index p to make up W_t grams of diluted material. While the radioactivity per se remains the same for each X-mer, the weight will be altered as prescribed by

$$W_{X,t} = W_{X,L} + W_{X,0} \quad (19)$$

where $W_{X,L}$ and $W_{X,0}$ give the respective weight contributions for labeled and unlabeled components. Thus

$$W_{X,t} = W_0 \cdot \frac{(1-p_0)^2}{p_0} \cdot xp_0^x + W_L \cdot \frac{(1-p)^2}{p} \cdot xp^x \quad (20)$$

which leads to the relation for the specific activity

$$R_X/W_{X,t} = \bar{R}_{X,t} = R_t \cdot \frac{(1-p)^2}{p} \cdot xp^x \cdot \left[W_0 \cdot \frac{(1-p_0)^2}{p_0} \cdot xp_0^x + W_L \cdot \frac{(1-p)^2}{p} \cdot xp^x \right]^{-1} = \frac{R_t}{W_L} \left\{ 1 + \frac{W_0}{W_L} \cdot \left(\frac{1-p_0}{1-p} \right)^2 \cdot \frac{p}{p_0} \cdot \left(\frac{p_0}{p} \right)^x \right\}^{-1} \quad (21)$$

The properties of $R_{X,t}$ may be conveniently studied if Eq. 21 is rewritten

$$\bar{R}_{X,t} = (R_t/W_L)(1 + Bs^{x-1})^{-1} \quad (22)$$

where

$$B = \frac{W_0}{W_L} \cdot \left(\frac{1-p_0}{1-p} \right)^2, \quad s = p_0/p \quad (23)$$

There are three distinct cases for Eq. 22, depending on the value of s.

A. The case $s = 1$ $(p_0 = p)$

$$\bar{R}_{X,t} = (R_t/W_L) \left(1 + \frac{W_0}{W_L} \right)^{-1} = R_t/(W_0 + W_L) \quad (24)$$

which agrees with our understanding of the specific activity distribution in a uniformly labeled polymer. The specific activity of each X-mer species is the same as that for the entire polymer.

B. The case $s < 1$ $(p_0 < p)$

$$\bar{R}_{X,t} = R_t/W_L \times \left\{ 1 + F \cdot \frac{W_0}{W_L} \exp\left[-\beta(x-1) \right] \right\}^{-1} \quad (25)$$

where

$$F = \left(\frac{1-p_0}{1-p} \right)^2 > 1, \beta = -\ln s \quad (26)$$

Thus $\bar{R}_{X,t}$ increases with X-mer size. At the lower end of size spectrum where $x = 1$, the specific activity is

$$\bar{R}_{X,t} = \frac{R_t}{W_L} \left(1 + F \cdot \frac{W_0}{W_L} \right)^{-1}, x = 1 = \frac{R_t}{W_L + FW_0} < \frac{R_t}{W_L + W_0} \quad (27)$$

which shows that the lower limit begins below the average value for the entire polymer as stated in Eq. 24. For the upper end of the spectrum as $x \to \infty$

$$\bar{R}_{X,t} = R_t/W_L, x \to \infty \quad (28)$$

which represents the net specific activity for the labeled portion of the mixture. Hence, the behavior of $\bar{R}_{X,t}$

for this case may be summarized by

$$\frac{R_t}{W_L + FW_0} \leq \bar{R}_{X,t} \leq \frac{R_t}{W_L},\ s < 1 \quad (29)$$

$x \rightarrow$

C. The case $s > 1$ $(p_0 > p)$

$$\bar{R}_{X,t} = R_t/W_L \times \left\{1 + F \cdot \frac{W_0}{W_L} \exp\left[\beta(x-1)\right]\right\}^{-1} \quad (30)$$

where $F < 1$ and $\beta = \ln s$.

so that $\bar{R}_{X,t}$ decreases with X-mer size. The specific activity at the lower end of the size spectrum for $x = 1$ is

$$\bar{R}_{X,t} = \frac{R_t}{W_L}\left(1 + F\,\frac{W_0}{W_L}\right)^{-1},\ x = 1 = \frac{R_t}{W_L + FW_0} > \frac{R_t}{W_L + W_0} \quad (31)$$

which is above that for the entire polymer. For the upper region of the size spectrum, as $x \rightarrow \infty$, $\bar{R}_{X,t} = 0$.
Thus this case can be summarized as

$$0 \leq \underset{\leftarrow x}{\bar{R}_{X,t}} \leq R_t/W_L,\ s > 1 \quad (32)$$

At this juncture, the general behavior of the specific activity distribution in the radiopolymer prepared by mixing batches of labeled and unlabeled material is, at least in principle, completely circumscribed. It is perfectly clear that wide variations in the skewing of the radioactivity toward either the low or high molecular weight species can arise in such preparations. In actual practice, however, it is virtually impossible at the present time to obtain the degree of resolution indicated by the foregoing discussion. Therefore it is worthwhile to reassess the results on the basis of some sort of weighted averaging which tends to level off extremes of specific activity.

The average specific activity may be defined as

$$(\bar{R}_{X,t})_{avg} = \sum_{x=1}^{x_0} R_X \Big/ \sum_{x=1}^{x_0} W_{x,t} \quad (33)$$

where obviously $x_0 \rightarrow \infty$ leads to the specific activity for the total distribution given by Eq. 24. At reasonably large levels of x_0, Eq. 33 becomes

$$(\bar{R}_{X,t})_{avg} = \frac{R_t \cdot \dfrac{(1-p)^2}{p} \cdot \displaystyle\int_{x=1}^{x_0} xe^{ax}\,dx}{W_0 \cdot \dfrac{(1-p_0)^2}{p_0} \displaystyle\int_{x=1}^{x_0} xe^{bx}\,dx + W_L \cdot \dfrac{(1-p)^2}{p} \displaystyle\int_{x=1}^{x_0} xe^{ax}\,dx} \quad (34)$$

where $a = ln\ p$, $b = ln\ p_0$.

Integrating and setting

$$P_1 = \frac{R_t(1-p)^2}{p(ln\ p)^2},\ P_2 = \frac{W_0(1-p_0)^2}{p_0(ln\ p_0)^2},\ P_3 = W_L(1-p)^2/p(ln\ p)^2$$
$$J_1 = p(ln\ p - 1),\ J_2 = p_0(ln\ p_0 - 1) \quad (35)$$

Then

$$(\bar{R}_{X,t})_{avg} = P_1[p^{x_0}(x_0\ ln\ p - 1) - J_1] \cdot \{P_2[p_0^{x_0}(x_0\ ln\ p_0 - 1) - J_2] + P_3[p^{x_0}(x_0\ ln\ p - 1) - J_1]\}^{-1} \quad (36)$$

which, in the form of Eq. 21, is

$$(\bar{R}_{X,t})_{avg} = (R_t/W_L) \cdot \left[1 + \frac{P_2}{P_3} \cdot \frac{p_0^{x_0}(x_0\ ln\ p_0 - 1) - J_2}{p^{x_0}(x_0\ ln\ p - 1) - J_1}\right]^{-1} \quad (37)$$

For $p = p_0$, Eq. 37 becomes

$$(\bar{R}_{X,t})_{avg} = R_t/(W_0 + W_L)$$

The evaluation for $p \neq p_0$ is not as simple. Since $x_0 \rightarrow \infty$ gives the same reduction for arbitrary values of p and p_0 as for $p = p_0$, the behavior of $(\bar{R}_{X,t})_{avg}$ may be deduced when $p_0 \neq p$ by inspecting Eq. 37 for $x_0 \rightarrow 1$. Thus

$$\frac{p_0^{x_0}(x_0\ ln\ p_0 - 1) - J_2}{p^{x_0}(x_0\ ln\ p - 1) - J_1} = \frac{0}{0} \text{ as } x_0 \rightarrow 1$$

The evaluation of this limit gives

$$\lim_{x_0 \rightarrow 1} \frac{p_0^{x_0}(x_0\ ln\ p_0 - 1) - J_2}{p^{x_0}(x_0\ ln\ p - 1) - J_1} = (p_0/p)\left(\frac{ln\ p_0}{ln\ p}\right)^2 \quad (38)$$

whereby Eq. 37 becomes

$$\underset{x_0 \rightarrow 1}{(\bar{R}_{X,t})_{avg}} = \frac{R_t}{W_L}\left[1 + \frac{W_0}{W_L} \cdot \left(\frac{1-p_0}{1-p}\right)^2\right]^{-1} \quad (39)$$

Hence, when $p_0 < p$, from Eq. 27

$$\underset{x \rightarrow 1}{(\bar{R}_{X,t})_{avg}} = \bar{R}_{X,t},\ F > 1 \quad (40)$$

And, for $p_0 > p$, from Eq. 31

$$\underset{x \rightarrow 1}{(\bar{R}_{X,t})_{avg}} = \bar{R}_{X,t},\ F < 1 \quad (41)$$

The general inferences about the distribution of specific activity based upon ideal resolution, as expressed by Eq. 21, are thus valid even for cruder methods of sampling the size distribution, for which Eq. 37 affords a quantitative basis of evaluation.

Conclusion

The preceding analyses should underscore the likelihood of serious error in the interpretation of counting data if the phenomenon under surveillance is characterized by fractionation. The following schemes can be invoked to ascertain whether fractionation is taking place.

If a doubly labeled polymer is provided such that one radionuclide directly measures the weight of collected fractions and another typifies the method of labeling which leads to nonuniform specific activity for different spectral ranges of the polymer, then a simple plot of one set of counting results versus the other, for identical samples, will be strictly linear only if no fractionation has occured. Where the resultant curve is nonlinear, judicious interpretation may yield some assessment of the nature of the fractionation process involved.

Where it may not be convenient, or desirable, to employ double tagging, the technique of mixing a large quantity of "inert" polymer with a small amount of uniformly labeled material can be carried out so as to produce a radiopolymer with severe skewing of activity in the low or high molecular weight segments. Thus, should one find diminished activity in either the very early or late collected samples, then this too would be strongly indicative of fractionation.

The logical question provoked by the foregoing discussion is this: if one cannot prepare a radiopolymer by any other means except by that which leads to complication should fractionation occur in its application, then how may the counting data be corrected to correlate with actual quantities of material sampled? This question may be reworded to express a fuller appreciation of its implications: how may our knowledge of the various modes of polymer fractionation (such as may be instituted by thermal diffusion, diffusion through membranes, chemical means, ultra-centrifugation, etc.) be enriched from well-conceived experiments based upon the application of those principles underlying the methodology of radiopolymers? Since the reply to this query necessarily involves detailed development of the complex theory of fractionation, it will be deferred for more appropriate consideration in forthcoming work.

* * *

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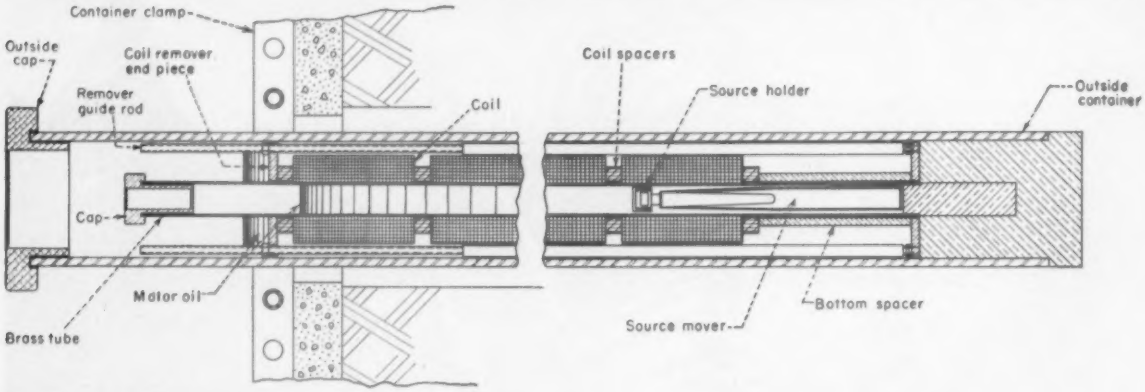

FIG. 1. Unit for shielding and storing 25-curie cobalt-60 source

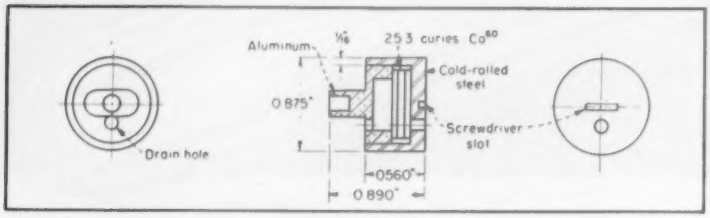

FIG. 2. Holder for 25-curie source

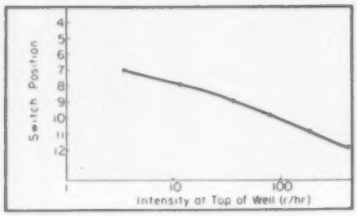

FIG. 3. Intensities at top of well

Economical Shielding for Multicurie Sources

By R. F. OBRYCKI, R. M. BALL, and W. C. DAVIDON
Nuclear Instrument and Chemical Corporation
Chicago, Illinois

An economical method for shielding and storing a 25-curie Co^{60} source consists of submerging the source holder in mineral oil in a pipe sunk in the ground. When in use, the source is raised to the top of the pipe by magnetic coils.

The complete apparatus is shown in Fig. 1. It is located in an isolated section of a basement, completely surrounded by concrete walls and a heavy door. Fig. 2 shows the source holder, which was loaded with three gold-plated Co^{60} disks 1 cm in diameter and 2 mm thick at Oak Ridge National Laboratory. Loading was done underwater with the aluminum piece held in a vise. The assembled source was shipped in an 860-lb lead container.

Construction of Apparatus

The outer pipe, 4 in. in diameter, was coated with pitch to prevent corrosion and sunk in the ground. This shaft is sealed at the bottom and has a tight cap at the top. In its center a brass pipe about 1 in. in diameter is placed, fitting into a slot in the bottom of the outer pipe. This center pipe also has a sealed bottom and a tightly capped top.

The source holder fits on top of a source mover that fits inside the brass pipe. The source mover, made of soft iron, serves as the plunger for the solenoid system used to move the source from the bottom to the top of the pipe. Magnetic coils around the brass pipe are energized in succession from bottom to top as a multiposition switch on the remotely located control box is rotated. The system is so designed that the source mover moves far enough into the upper of two coils energized successively that it continues moving up when power to the lower coil is removed.

The coils, designed and constructed for d-c operation by a local supplier,* are mounted on a frame that permits them to be removed or replaced without moving the center brass pipe.

Both the iron and brass pipes were filled with DC 200 oil (0.65 centipoise). In the outer pipe, this oil insulates and cools the magnetic coils, allowing one coil to hold the source in a raised position for many days without overheating. In the brass pipe, the oil attenuates the gamma radiation, reducing the intensity to about 2 mr/hr at 65 in. This oil also keeps the source from moving too fast during operation.

Loading and Operation

Original plans called for removing the source holder from the shipping container with magnetic tongs. But

* Central Transformer Co., Chicago, Ill.

the holder was shipped with the iron part down, and mechanical tongs were needed to remove the source from its position in the container. Once removed, it was handled with the magnetic tongs and dropped into a funnel that guided it into the brass pipe. There it came to rest on the source mover.

The two pipes were sealed, and the unit was ready for operation. Radiation is continuously monitored by two commercial instruments (NICC models 2610A and 2584). Figure 3 shows radiation intensities for various positions of the stepping switch used to control operation of the lifting coils.

Criteria Unit Meets

The prime consideration in design of such a unit is the safety of personnel. This safety is provided by:

1. Source in sealed container. Not only is the source holder threaded, but it is sealed within the central brass pipe so that possible damage from leakage is doubly prevented.

2. Easy, safe loading. Except for turning the source holder over, loading went as planned and took about 15 sec. The operation was conducted about 10 ft from the source by one person. Total exposure was about 60 mr.

3. Adequate shielding. With the source at the bottom, storage position, radiation directly over the hole is about 2 mr/hr. Everywhere else it is less.

4. Tamperproof, fail-safe mechanism. The control box is 25 ft from unit, and the power switch is key operated. If source is raised too fast, or if any failure occurs, the source falls to the bottom of the unit. Electrical lifting makes it easy to use interlocks.

5. Controllable dosage. Intensity can be varied by raising source to different heights and by varying distance from irradiated object to top of unit. The radiation beam, collimated by the earth surrounding pipe, is well defined and reproducible.

6. Safe removal, disposal of source. The source can be removed by using magnetic tongs. If necessary, the entire center pipe could be disposed of without unsealing the system.

7. Easy, safe repair. The only parts that seem capable of failure are the coils, the power supply, or switching. The latter two are external to the unit, and the coils can be removed without raising the source or disturbing the center pipe.

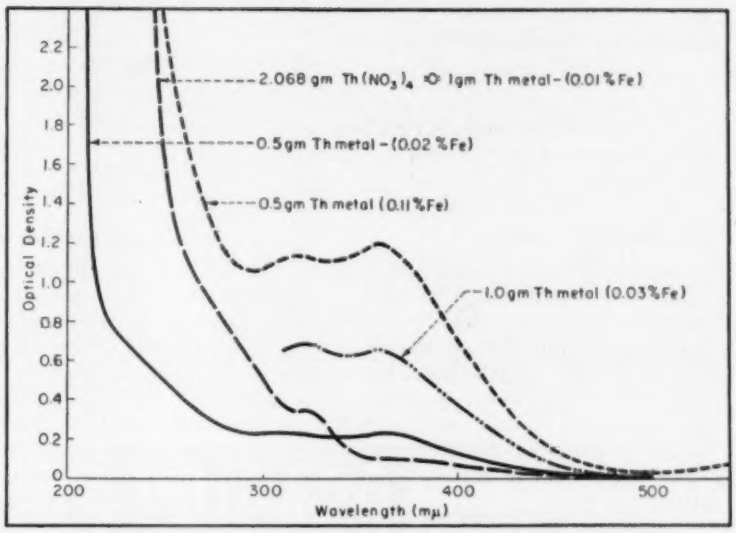

FIG. 1. Spectrophotometric curves showing presence of Fe in Th samples (hydrochloric acid method). Each 25-ml sample contains 8 mg Na_2SiF_6 + 16 mg H_3BO_3

Method for Determination of Iron in Thorium Metal and Compounds

By LOUIS SILVERMAN and KATHERINE TREGO
Atomic Energy Research Department, North American Aviation, Inc. Downey, California

Thorium was formerly of industrial importance in the preparation of incandescent mantles, but present interest is directed toward its radioactive properties. Thorium metal and thorium alloys are now actively being investigated, and chemical determination of impurities is therefore necessary. Iron, one of the expected contaminants, is usually present in small amounts.

The determination of iron as ferric chloride in 1:1 hydrochloric acid solution has been found useful (*1–3*). The technique is without serious complications since iron may easily be obtained in the ferric condition in 1:1 hydrochloric acid solution; in particular examples, iron may be determined without preliminary separations. The precision is about 0.02 mg (0.002%) with the method described here.

In the visible range, several chlorides are markedly colored in hydrochloric acid solution (*4*). Besides ferric chloride (yellow), there are copper (yellow), cobalt (blue), quadrivalent iridium (brown), trivalent rhodium (rose-red), as well as the less intense gold, palladium, platinum, nickel and ruthenium. Higher concentrations of zinc, mercury and sulfate may decrease the intensity of the iron color. But, in the particular case of purified thorium metal and thorium compounds, any of the elements just listed would be in small quantities, and would not interfere with iron determination.

Thorium chloride is of prime interest. The spectrophotometric curves for several samples of thorium chloride (0.5–1 gm of thorium per 25 ml of solution) are drawn in Fig. 1. Absorbancy between 400 and 500 mμ is small for thorium chloride; in the near ultraviolet range the low absorbancy for thorium chloride may easily be compensated (Fig. 1). Consequently, the determination of iron in thorium by the HCL method was investigated.

Thorium metal may be dissolved

Analytic Procedure for Fe Determination

Special Apparatus and Reagents

Beckman spectrophotometer, DU, with 10-mm cells. Boric acid, c.p. Hydrochloric acid solutions, equal volumes of acid and water made up in large quantity. Hydrogen peroxide, 30%, c.p. Sodium fluosilicate, c.p., iron-free; Na_2SiF_6.

Solution Preparation

Solution of thorium metal. Transfer a 1-gm sample (chips) to a 100-ml beaker and add 8 mg of sodium fluosilicate and 10 ml of 1:1 hydrochloric acid. The reaction is quite rapid at first, but the solution must be warmed to help dissolve the slower acting particles (oxide).

Solution of ignited thorium oxide. Transfer the sample to a 150-ml Erlenmeyer flask, add 8 mg of sodium fluosilicate and 10 ml of hydrochloric acid (specific gravity 1.2). Warm under an air condenser until the sample completely dissolves.

Preparation of sample. After the sample has dissolved, add 16 mg of boric acid and 1 ml of 30% hydrogen peroxide. Evaporate to dryness, without splattering. Cool. Take up the residue in 10 ml of 1:1 hydrochloric acid solution. Transfer to a 25-ml volumetric flask and dilute to the mark with 1:1 hydrochloric acid solution. If there is a dark residue, usually carbon, filter through paper into the volumetric flask and wash with 1:1 acid.

Read the optical density at a selected wavelength such as 342.5 or 420 mμ, compared to water at 0.0 density. Subtract the blank, if any, read from a solution containing the original reagents of sodium fluosilicate, boric acid, hydrogen peroxide and 1 gm of thorium salt (iron-free). From the corrected reading, obtain the iron value on the calibration curve.

Calibration and Spectrophotometric Curves

A sample of thorium nitrate is used as the ultimate thorium standard. Since the degree of hydration is uncertain, the thorium content may be checked by burning to oxide. The sample of thorium nitrate (water soluble) equivalent to 1 gm of thorium metal, is treated as for thorium metal in the procedure, with the exception that an additional hydrochloric acid evaporation is performed to remove nitrate. Spectrophotometric curves of thorium samples are shown in Fig. 1. In Fig. 2 the following curves are shown: reagents, 0.2 mg Fe plus reagents, 0.2 mg Fe plus thorium, and 1 mg Fe plus thorium. Figure 3 shows superimposed curves of "mg-iron" alone and "mg-iron" plus thorium at 342.5 mμ (*8*) and 420 mμ (*9*), plotted against optical density. All four graphs conform to Beer's Law in the range of 0–0.5 mg Fe.

Spectrophotometric curves are also plotted for elements that might be present in thorium as impurities; these are shown in Figs. 4, 5, and 6.

completely by hydrochloric acid with the aid of a little fluoride or silicofluoride as catalyst (*5–7*). Nitric acid plus catalyst is just a fair solvent, and, by repeated evaporation with hydrochloric acid, the chloride is obtained.

Thorium salts are converted to chloride by first igniting to the oxide, with subsequent solution in hydrochloric acid plus catalyst.

Interference by Thorium

Thorium chloride solution in 1:1 hydrochloric acid solution is colorless in the visible range (Fig. 1), and forms neither colored complexes nor precipitates with cations in this acid solution. Furthermore, in the near ultraviolet region, the optical density of the thorium chloride solution is low. Thorium itself, therefore, should provide no interference in the determination of impurity-iron in chloride solution.

Proof that thorium chloride does not interfere in the absorbancy of ferric chloride solution is shown in Fig. 3, where the ferric chloride absorbency plot is the same whether thorium is present or absent (0–0.5 mg Fe). Thus iron can be determined in the presence of thorium if thorium is present at a concentration of 4 gm per 100 ml of solution. Since there is small, but nevertheless definite, absorption by thorium chloride in the near ultraviolet region, it is optional to subtract a blank for thorium chloride, or to use pure thorium chloride in the blank cell.

The necessary reagents, hydrochloric acid, sodium fluosilicate, boric acid and hydrogen peroxide (Fig. 2) show little tendency for absorption above 290 mμ, but at shorter wavelengths a blank must be subtracted.

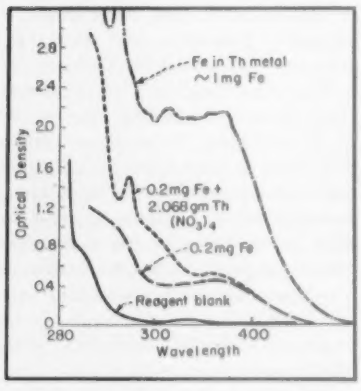

FIG. 2. Optical density vs. wavelength

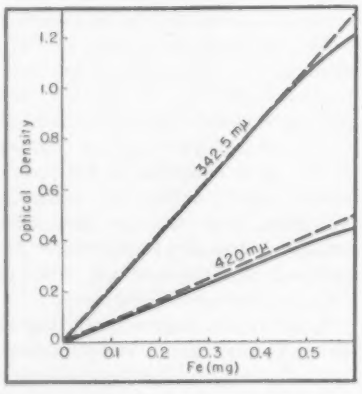

FIG. 3. Calibration of Fe:HCl method

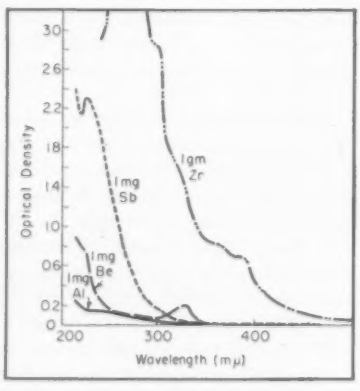

FIG. 4. Optical density vs. wavelength

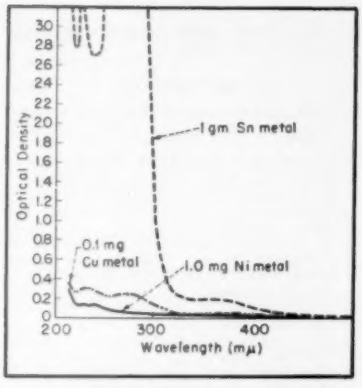

FIG. 5. Optical density vs. wavelength

The two graphs (Fig. 3) are not wavelengths selectively chosen, nor are they picked at random. One wavelength represents a point in the visible spectrum (420 mμ). This wavelength is suitable for filter photometers; it is a wavelength where iron solutions follow Beer's law, and at this wavelength the optical density is adequate for quantitative work. Furthermore, the optical density of solutions of metals which might be associated with thorium (tin, Fig. 5; lead, Fig. 6; zirconium, Fig. 4) are negligible.

The other wavelength, 342.5 mμ, coincides with the bottom of a plateau (Fig. 2) in the near ultraviolet. This wavelength would be available to instruments such as a Beckman B. Small amounts of common elements such as aluminum, antimony, beryllium, copper, nickel or tin would not influence the determination.

The A.S.T.M. procedure for iron (*1*) selected 370 mμ because copper interference is a minimum there (Fig. 5).

Iron Determination

The suitability of this method as a standard routine procedure for the determination of iron in thorium metal

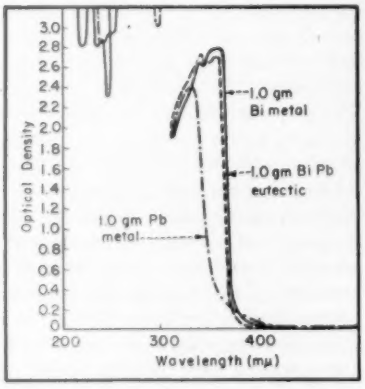

FIG. 6. Optical density vs. wavelength

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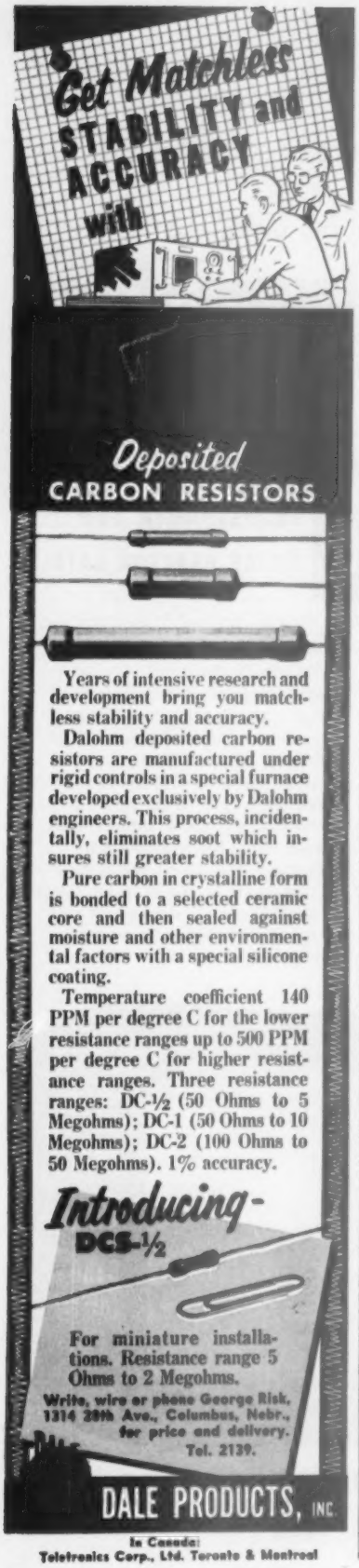
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and thorium salts is based upon the results obtained from synthetic solutions. The coincidence of two curves for iron solutions, one with and one without thorium, indicates a series of 10 precision checks. In view of the fact that the determination of iron as ferric chloride is not a new method, and also from the fact that (insofar as absorbancy is concerned) the ferric chloride-thorium solution acts as if ferric chloride alone were present, it may then be accepted that the procedure proposed for iron in thorium is adequate.

* * *

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Experimental Method for Determination of Counting Geometry

By BEN KALMON
Lewis Flight Propulsion Laboratory
*National Advisory Committee for Aeronautics, Cleveland, Ohio**

To determine the strength of a radioactive source by any of the standard methods, the "geometry" of the source-counter arrangement, i.e., the fraction of the particles emitted by the source that enters the sensitive region of the counter, must be known. If absorption and scattering in the region between source and counter are ignored, this quantity can be calculated on the basis of purely geometric considerations. This was done for a cylindrically symmetrical case involving a thin flat source, by Blachman† whose results appear in the form of a series expansion involving the usual dimensional parameters of the system, viz., source and counter diameters, 2ρ and $2R$, respectively, and source-to-counter distance, z.

In an experimental method due to Healy, *et al.*,‡ a thin source whose size is small compared to the diameter of an axially symmetrical end-window counter, is displaced a variable distance r along a radius perpendicular to the axis of symmetry of the system. From the measured counting rate as a function of $r\,(0 \leq r \leq \rho)$ the geometry of a radially symmetrical, thin homogeneous source of diameter 2ρ at a distance z from the counter, can be obtained by an integration procedure. If the counting rate for a point source of intensity s (total number of particles emitted per second) is designated as $f(r, z)$, then the geometry g for an extended source of the sort contemplated is

$$g = 2\int_0^{\rho} f(r, z)\, r dr/(s\rho^2)$$

provided the counter is 100% efficient.

Another experimental method of determining the geometry of a configuration of this type is presented here. It does not require the use of a "point source" (and in principle can be applied also to the determination of the geometry of any thin source distributed uniformly on a developable surface). To carry out the determination of the geometry by the present method, a thin uniform source of this type is realized by soaking filter paper in a radioactive solution. Essentially, disks of radii ranging from ρ down to ρ', small compared to R and z, are made out of this material. The counting rate is determined when each of these is placed at a given distance z from the counter. If the counting rate per unit area is plotted against the area of the disk, one is able to extrapolate to the value cor-

*Present Address: Goodyear Atomic Corp., Piketown, Ohio.

† B. P. Burtt, Nucleonics **5,** No. 2, 43 (1949).

‡ J. W. Healy, L. C. Schwendiman, R. C. Thorburn. Counter calibrations in the health instrument methods group, HW-18258 (1950).

responding to a point source located on the axis of the system. By comparing this value with that of an extended source of the same strength per unit area, the geometry of the extended source can be obtained in terms of that of a point source.

Experimental Procedure

The Geiger tube used in the measurements was a conventional bell-shaped end-window counter, with a diameter of 1.125 in. and a 2.0-mg/cm² mica window. The source was mounted so that it could be located at several positions along the axis of the tube at a known distance from the mica window. The entire assembly was shielded by 1.5 in. of lead.

The source was prepared by immersing a sheet of filter paper, 2.5 in. in diameter, into an active solution of natural uranyl nitrate. To assure a uniform distribution, the filter paper was allowed to dry in a horizontal position on the source holder.

For the sake of convenience, the diameter of the source was fixed by covering the filter paper with a mask consisting of a piece of aluminum 823 mg/cm² thick with a circular aperture of appropriate size. This thickness is sufficient to absorb the highest energy beta rays emitted by the source. To minimize back-scattering, the filter paper was supported on its periphery only.

The aperture diameters ranged from 0.25 to 2 in. in increments of 0.25 in. The measured counting rates were corrected by subtracting from them the counting rate obtained with the source covered by a solid aluminum plate of the same thickness.

As a check on the uniformity of the source, it was cut into ten pieces after the measurements were done, and an area of each piece defined by the mask with the 0.25-in. diameter aperture was exposed to the counter. The individual counting rates agreed to within ±2.5% of the arithmetical mean value obtained from the ten pieces.

Results and Conclusions

Plots were made of counting rates per unit area, C, against area and each curve extrapolated to zero area as shown in Fig. 1. For convenience, the data are represented in the form of a semilogarithmic plot because of the large range of values involved. The counting rate per unit area is nearly a linear function of the area, and thus the extrapolation is simple to carry out;

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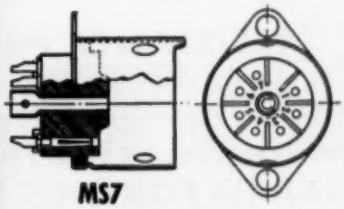
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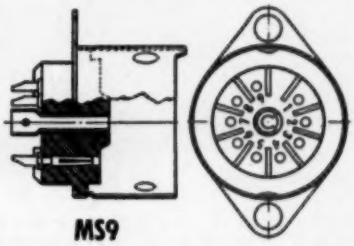
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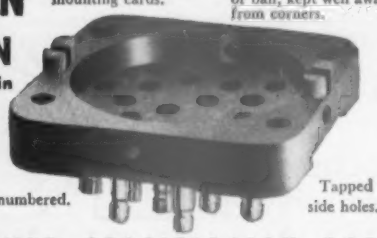

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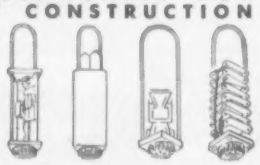

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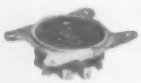

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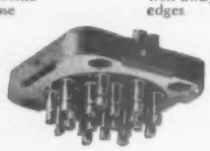

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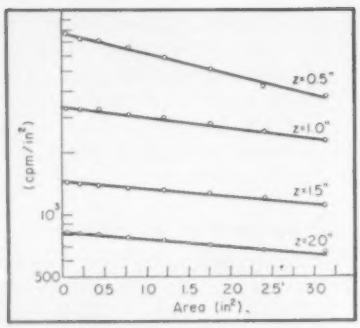

FIG. 1. Counting rate per unit area of source as function of its total area

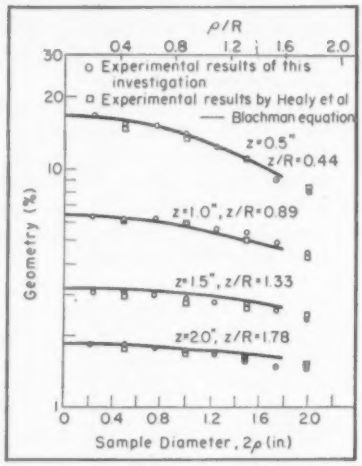

FIG. 2. Comparison of present experiment with previous investigations

the extrapolated value, C_0, was taken as the counting rate per unit area of an an infinitesimally small source (point source). The geometry of a point source is

$$g_{p.s.} = \tfrac{1}{2}[1 - (1 + \beta)^{-\frac{1}{2}}] \quad (1)$$

where

$$\beta = R^2/z^2 \quad (2)$$

The geometry, g, for a source of diameter 2ρ is

$$g = g_{p.s.} C/C_0 \quad (3)$$

Values for g for source-to-window distances of 0.5, 1.0, 1.5, and 2.0 in. were determined in this manner. The results are shown in Fig. 2. This figure also contains the values obtained by Healy *et al.*, as interpolated to agree with the values of the parameters ρ and z used in this investigation. In both cases the tube window was the same size ($2R$ = 1.125 in. diameter). The geometry for the values of ρ, R and z used in this investigation, as calculated by the use of Blachman's equation, are also included.

An inspection of Fig. 2 shows that all

the results agree within limits of experimental error.

* * *

The author is indebted to Mr. Benjamin Welber and Dr. Gerhart Groetzinger for valuable discussions.

THE COVER

Laboratory Studies of Uranium Deposits

Geological occurrence of uranium ores on the Colorado Plateau has been the subject of extensive field and laboratory studies.* Some of the apparatus used at Amherst College, Amherst, Mass., is shown on the cover.

After field tests, the first experimental operation was to investigate fluvial deposits of heavy minerals. On a swimming pool floor a 10½ by 60 ft area was enclosed with wooden planks 12 in. high. This box was filled with glacial lake silt to constitute the bed of an intermittently flowing stream and the highlands source of water and silt. Fog nozzles above the highlands were used to simulate rainfall.

Uranium-bearing samarskite was used as the heavy mineral deposit. A vein of this ore was simulated in the highlands transverse to the stream. A G-M counter was used to plot distribution of the radioactive samarskite after each "rainfall."

Another phase of these experiments was a quantitative study of the relation between size and sphericity of detritus (silt to conglomerate) and distance it is carried by a stream. Since there is little difference between moving water over a stream bed or moving the bed under the water, the 8-ft diameter wheel was used for these studies. Equivalent water speeds of 2–14 mph were obtained, and detritus size and sphericity were measured at 10-mile intervals of travel for a total of 80 miles.

Results. Good correlation was obtained with field studies. The only explanation of ore distribution that has no anomalies is the one attributing the ore to slight redistribution by artesian groundwater. Plateau ores occur in or adjacent to fluviatile sediments and generally avoid flood plain and aeolian accumulations. The origins of uranium and vanadium ores seem to be disconnected problems.

* A complete report of these studies is given by G. W. Bain *et al.* in "Experimental Simulation of Plateau Type Uranium Deposits," RMO-44 (1953).

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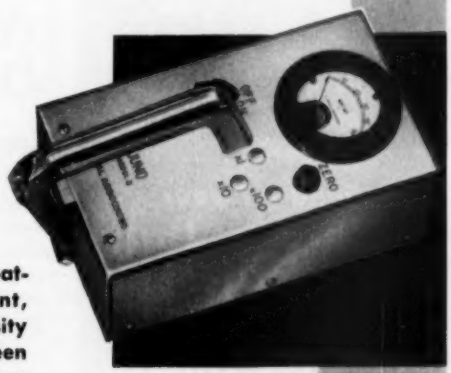

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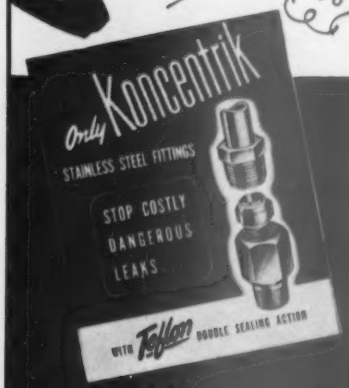

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NUCLEAR ENGINEERING

Contamination and Decontamination of Rubber Gloves

By A. P. TALBOYS and S. S. COPP
Johns Hopkins University
Baltimore, Maryland

Rubber gloves used to avoid contamination of the hands when working with radioactive substances are often discarded if they become contaminated. However, in large scale operations this becomes a rather costly procedure. In view of this, a laboratory investigation was undertaken here to study the extent of contamination by several different isotopes, and to find effective means of decontamination to permit reuse of the gloves.

Four representative types of rubber gloves were used in the tests:

1. **Surgeon's gloves.** Light weight, high-quality natural rubber.
2. **Yellow latex gloves.** Medium weight, natural rubber.
3. **Neoprene gloves.** Heavy duty, black neoprene with roughened fingers.
4. **Canner's gloves.** Thin, low-quality rubber with roughened fingers.

Contamination Tests

Samples cut from the gloves were suspended vertically from wire hooks in solutions of carrier-free I^{131} (NaI), and isotopically diluted P^{32} (H_3PO_4) and Sr^{89} [$Sr(No_3)_2$]. The *p*H of the solutions was adjusted with HCl or NaOH and measured with a *p*H meter.

Following immersion, the sample pieces were dipped momentarily in distilled water to remove adhering droplets of active solution and then were air dried. Placed in large aluminum planchets, the samples were counted with an end-window G-M tube.

Rate of contamination. All samples adsorbed the radioisotopes at a low rate initially. But P^{32}, and to a lesser extent Sr^{89}, was taken up at an increasingly greater rate until a maximum level of contamination was reached in about 30 hr. High levels of contamination were not reached with I^{131}.

Importance of *p*H. Peaks in the uptake vs. *p*H curves occurred around *p*H 4 and 11 for P^{32}. With Sr^{89}, little contamination was present in the acid range, but uptake increased rapidly with alkalinity. Uptake of I^{131} was favored by strongly acid conditions.

Effect of concentration. Contamination levels increased with concentration of P^{32}, leveling off at the highest concentrations (35–40 $\mu c/1$) used in these tests. The surgeon's and yellow latex glove samples absorbed less P^{32} than did the neoprene and canner's glove samples. Roughened portions of the canner's gloves took up the most activity.

In tests with Sr^{89} and I^{131}, only minor differences among the various samples were observed.

Temperature effects. Increase of temperature up to 94°C accelerated uptake of P^{32} and Sr^{89}, but had only a slight effect on I^{131} uptake.

Decontamination Tests

Contaminated samples were subjected to three decontamination methods:

1. **Simple immersion.** Desorbing action of various solutions and decontaminating agents on samples.
2. **Immersion plus agitation.** Desorption aided by vigorous stirring and movement of samples in solutions, simulating laundering.
3. **Scrubbing.** Mechanical action of brushing combined with desorbing action of the solutions.

Decontaminating solutions and agents used included cold water, hot water, acids, alkali, detergent (DuRite, formula 85), citric acid, Versene, Igepal, and other chemicals.

Results. An ordinary anionic detergent and regular Versene were consistently the most effective decontaminating agents. Surgeon's gloves proved superior in all tests, and I^{131} proved to be the most difficult to remove from contaminated samples. Agitation of the samples for 15-min periods was considerably more effective than simple immersion (86% removal compared to 60% for P^{32}), and in most cases almost as effective as scrubbing (up to 94% removal).

Ordinary laundering procedures appear feasible for decontamination of rubber gloves. Where only a limited number of gloves are involved, scrubbing should give the best results possible.

* * *

This article is based on NYO-4519 (1952), which contains a more quantitative report of this work.

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BOOKS

Meson Physics

By ROBERTE. MARSHAK (McGraw-Hill Book Co., Inc., New York, 1952, viii + 378 pages, $7.50). Reviewed by JOHN A. WHEELER, Palmer Physical Laboratory, Princeton University, Princeton, N. J.

Since Yukawa's proposal in 1935 of an analogy between nuclear and electromagnetic forces, with mesons forming the elementary quanta of energy of the one field, just as photons constitute the quanta of the other field, enormous advances have taken place in meson physics, both theoretically and experimentally. With roughly forty papers a month appearing on the subject, Professor Marshak's up-to-date summary is most helpful, both to the specialist working in the field and to the general physicist who wishes a summary of findings to date.

Beginning with the single production of π-mesons in photon-nucleon, nucleon-nucleon, and nuclear encounters, the book goes on to the properties of π- and μ-mesons and the production and interactions of π-mesons at cosmic-ray energies, and ends with a summary of new particles and new processes up to July, 1952.

At each stage, a detailed comparison is made between the observations and the results obtained from various versions of the so-called weak-coupling and strong-coupling meson theories. On this score, the treatment is thoroughly matter of fact; quite appropriately no effort is made to enter into deeper questions of the foundations of meson theory. Instead, the reader is left with the justified impression that present meson theory has a qualitative correspondence with observation, and is on this account most illuminating; but is not in all instances quantitatively trustworthy.

Topics covered include kinematics of single meson production in photon-nucleon collisions; weak-coupling theory of photomesic production; classical theory of photomesic production; electron production of π-mesons; kinematics of single meson production in nucleon-nucleon collisions; weak-coupling theory of single π-meson production in nucleon-nucleon collisions; kinematics of nuclear production of π-mesons; nuclear effects; production of charged π-mesons in photon-nucleus collisions; production of π^0-mesons in photon nucleus collisions; production of

charged π-mesons in nucleon-nucleus collisions; production of π^0-mesons in nucleon-nucleus collisions; masses of π-mesons; decay of π-mesons; spins, statistics, and parities of π-mesons; capture of slow negative mesons; structure of mesic atoms; nuclear absorption of slow π^--mesons.

Also decay and absorption of slow μ^--mesons; mass of μ-meson; decay of μ-meson; spin of μ-meson; nuclear interaction of μ-mesons; interaction of π-mesons with protons and deuterons; interaction of π-mesons with heavy nuclei at moderate and high energies; theories of plural and multiple production of π-mesons; kinematics of multiple meson production; experimental evidence for plural and multiple production of π-mesons; Auger showers; production and annihilation of antinucleons; heavy mesons; and V-particles.

The extensive graphs and tables in this monograph, together with the author's careful analysis and assessment of the subject, make it an excellent starting point and reference book for anyone working in the field.

BOOKS RECEIVED

Mr. Tompkins Learns the Facts of Life, by George Gamow, Cambridge University Press, New York, 1953, xi + 88 pages, $2.75. Mr. Tompkins, the hero of two previous books by Professor Gamow, learns something of biology in this popular account of what goes on in the bloodstream, what genetics is about, and how the brain works.

Refractory Hard Metals, by Paul Schwarzkopf and Richard Kieffer with Werner Leszynski and Fritz Benesovsky, The Macmillan Co., New York, 1953, xi + 447 pages, $10. (*To be reviewed.*)

ALSO OF NOTE

Table of the Arctan x, 2nd ed. (National Bureau of Standards Applied Mathematics Series 26). In addition to continuing the table of arctan x, the present volume includes coefficients for interpolation and a conversion table that converts radians to degrees and degrees to radians. *GPO, Washington, 25, D. C., $1.75.*

Zirconium, A Bibliography of Unclassified Report Literature (TID-3010, Supplement 1). Abstracts of 95 reports in the unclassified literature available up to March 15, 1953. *Office of Technical Services, Department of Commerce, Washington 25, D. C., $0.20.*

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NEWS

House Committee Approves AEC Budget of $1.06-Billion for Fiscal 1954; Cuts $39-Million from Request

The House Appropriations Committee slashed $39-million from President Eisenhower's request for appropriations for the Atomic Energy Commission for fiscal 1954. By the normal processes of Congress, the appropriations bill will now be passed by the House and Senate with no further changes.

The original Truman budget called for $1,593-million for AEC. The Eisenhower revision of the budget brought this figure down to $1,096-million (NU, June '53, p. 86), and the final version, approved by the committee, calls for $1,058-million.

Details of the Eisenhower request are given in the tables below, with last year's figures shown for comparison. No breakdown on plant and equipment appropriations have been released. Both Eisenhower and the Committee allowed the same amount, $166-million, for plant and equipment.

The major portion of the cut of $39-million came from money carried on AEC books as working capital, $33-million, which was ordered returned to the Treasury.

The other cuts made in the budget were as follows: community operation, $69,000; program direction and administration, $2,706,000; and inventories, $2,682,000.

AEC Plant and Equipment Budget ($-thousands)

	1953	*1954*
Raw materials	1,400	9,105
Fissionable materials	2,624,721	533,487
Weapons	59,873	86,496
Reactor development	42,927	32,478
Physical research	4,203	2,430
Biology and medicine	856	391
Community	8,652	5,633
Administrative	14	0
Equipment not included in construction projects	27,812	29,616
Total obligations	2,770,458	699,636
Unobligated balance carried forward from prior year	500,083	−533,636
Total appropriation	3,270,541	166,000

Issues Now Clear on Changes in McMahon Act

The principal issues to be faced in Congressional hearings on revision of the Atomic Energy Act of 1946 have been made clear by the Government and industry officials who have gone on the record with opinions and ideas on the subject.

At this writing, the Joint Congressional Committee on Atomic Energy is holding executive sessions, with testimony already having been taken from the Atomic Energy Commission, the Joint Chiefs of Staff, the State Department, and private industry. When this issue appears, it is expected that public hearings will have been in session for about a week, with many of the same witnesses performing again.

Some of the questions that have been raised are:

1. Do we have enough of a potential for supplies of fissionable material to foster development of nuclear power for industrial use?

2. What would the effect of a private nuclear power industry be on negotiations for international control of atomic energy?

3. Would the national security be endangered if industry were to take on considerable responsibility for nuclear power development?

4. What about the physical security of vital plants and the security of vital information?

On June 2, the Joint Committee met with representatives of the Joint Chiefs of Staff to consider the effects of the development of nuclear power on the military use of fissionable materials. The representatives of the Joint Chiefs recommended that any legislative changes to further nuclear power development should include adequate safeguards to protect military claims on fissionable materials, and concurred in the view that the development of nuclear power by private enterprise would be beneficial to the military services and to the national security.

It was further stated that in the event private enterprise did not under-

Operating Costs for AEC Programs ($-thousands)

	1953	*1954*
RAW SOURCE AND FISSIONABLE MATERIALS		
Procurement, production		
Raw source and feed materials	102,727	178,700
Fissionable materials, special products	136,127	205,767
Process, development		
Raw source and feed materials	7,486	8,069
Fissionable materials, special products	35,035	31,402
TOTAL	281,375	423,938
WEAPONS	253,068	299,833
REACTOR DEVELOPMENT		
Production and power reactors	18,141	24,700
Ship propulsion program	35,725	26,750
Aircraft propulsion program	17,725	15,200
Other reactors	37	0
General development	12,660	12,500
Operation of specific reactors, processing plants and facilities	8,575	8,600
TOTAL	92,862	87,750
PHYSICAL RESEARCH		
Isotope program	564	564
Physics research	18,445	18,295
Chemistry research	14,394	14,654
Metallurgy and materials research	4,634	4,634
Mathematics	100	250
University training	763	503
TOTAL	38,900	38,900
BIOLOGY AND MEDICINE		
Cancer research	2,479	2,974
General research	6,786	6,993
Biological research	10,861	11,276
Biophysical research	4,360	4,616
University and special training	714	706
TOTAL	25,200	26,565

take rapid development of nuclear power, it was the view of the Joint Chiefs that the Government should continue to push ahead in the field.

On June 4, the Joint Committee met with Under Secretary of State Walter B. Smith to discuss foreign policy implications of legislation designed to foster development of nuclear power. Smith's statement touched on the importance of maintaining United States leadership in the field of atomic energy, and the procurement of raw materials.

He also stated that it was the view of the State Department that any legislative changes designed to further the development of nuclear power should take into account the Government's continuing interest in bringing about international control of atomic energy.

Group Would Pay Reactor Costs if Act is Changed

The Dow Chemical Co.—Detroit Edison Co. nuclear power group will invest its own money in the building of a nuclear power plant if the Atomic Energy Act is revised to permit this. The group has also stated that it would not require any substantial Federal subsidy or guarantee for this program.

This was revealed last month in statements made by Walker Cisler, president of Detroit Edison, and Dr. John Grebe, of Dow, in secret hearings before the Joint Congressional Committee on Atomic Energy.

Earlier last month, in a talk before the Edison Electric Institute at Atlantic City, Cisler said, "The development of atomic fuels for the generation of electric power is rightfully the responsibility of the electric power industry. The electric power industry should largely assume the costs of the development. The industry, in this sense, includes not only the electric power systems themselves, but also the power equipment manufacturers, the engineering and construction fields, power consumers, etc."

"Construction, testing and experimentation [in nuclear power technology]," Cisler added, "will require the expenditure of substantial sums of money. This should be regarded in the same light as other research and development efforts carried on since the beginnings of the electric industry."

Pentagon Economy Wave Caused Confusion in AEC Power Plans; Large Ship Reactor Cancelled

The road which the United States is taking in the pursuit of atomic power for industrial use is by no means a bee-line. Partly because of a military requirement for nuclear propulsion, and partly because of the fear that Congress would not appropriate funds for a purely civilian, peacetime atomic power unit, the Atomic Energy Commission is not following the direct road to industrial atomic power. Instead, it has taken the military route, placing emphasis upon mobile propulsion units.

As Chairman of AEC, Gordon Dean stated that the development of industrial atomic power would benefit from the military reactor program. "The dividend in knowledge we will gain," he said, "will have a direct and immediate application to our effort to produce commercial civilian power." In view of recent shake-ups that have occurred in the military reactor program, it can be seriously questioned how direct and how immediate this application will be.

The shake-ups in the military reactor program have not been fully reported. They have resulted from high-level decisions in the Pentagon to reduce defense expenditures. Enough can be gathered to piece together a fairly complete picture of what has happened, but to see how the pieces fit together we must look at what reactors were planned prior to the Pentagon's cutback or stretch-out in military spending.

The military reactor types before the shake-up can be classified under three headings appropriate to each of the services:

Naval Reactors

There are three reactors in this group.

Submarine thermal reactor (STR). A land-based prototype of this naval propulsion plant has been built into a simulated submarine hull at Arco, Idaho. On May 1, 1953 this reactor went into operation. An improved version of the Arco design is being built by Westinghouse Electric Corp. and will be incorporated into the U.S.S. Nautilus. The latter is scheduled to hit the water sometime late next year.

Submarine intermediate reactor (SIR). The land-based unit for this power plant is being built by General Electric Co. In contrast to the water-cooled STR design, the SIR unit will use a liquid-metal coolant. Construction of the prototype SIR unit is under way.

Large ship reactor (CVR). About one year ago, the AEC awarded a contract, with Navy Bureau of Ships participation, to Westinghouse to design and construct a large atomic power unit for surface ship propulsion. It was intended as a prototype for a single-shaft drive of the third supercarrier authorized by Congress. It is known that AEC looked upon this reactor as a two-in-one design. The Navy could use it for testing out its carrier propulsion design, and AEC would gain practical experience with it as a prototype of a civilian industrial power producer.

Air Force Reactors

The Air Force and AEC have entered into a contract with the Gas Turbine Division of General Electric (Lockland, Ohio, plant) to design and develop a reactor for powering an aircraft. This contract replaces the previous ill-fated NEPA project of the Air Force.

A second contract was negotiated with Pratt and Whitney.

Gordon Dean recently revealed that the Air Force objective in nuclear propulsion was "simply having something in the air by some time in 1958, even though it was never the ultimate plane—something that could go 300 miles an hour at 15,000-ft altitude."

Army Reactors

The Army is studying the possibility of using reactors to supply power for its isolated bases. However, as an Army officer stated this spring "this is a Johnny-come-lately thing. There is virtually no money in the army

budget for this study." Thus, so far as this report is concerned, we can disregard the Army reactors.

This, then, was how things shaped up early this spring with the military focusing their requirements upon four different reactors. And because AEC had patterned its reactor program to conform to a military profile, the whole AEC reactor program, so far as power is concerned, focused on these same four reactors. Because of the design nature of these reactors, only one, CVR, held any promise of contributing directly to an industrial atomic power plant.

In May of this year, Defense Secretary Wilson, having sharpened his economy ax, swung it in the direction of military reactors. There is no indication, judging from what can be deduced in Washington, that the economy blows were all well aimed. In one move, Secretary Wilson lopped some $7-million off the funds budgeted for the next fiscal year in aircraft nuclear projects. Commented Mr. Wilson: "If everything worked out as the scientists planned, it would have been a bum airplane." Actually the $7-million slash was not protested by the Air Force since the project that was cut back had been one that embarrassed its backers, and, with economy as the excuse, it was simple to ease out of what promised to be a dead-end project. Thus the cuts in the aircraft reactor budget are not serious. But the budget cut-back in naval reactors is serious and directly affects AEC hopes for industrial atomic power.

As a result of a defense department review of its military reactor program, it recommended to the National Security Council that work on a prototype for CVR should be stopped. It is reported that Mr. Wilson stated that ultimately the power plant for the super-carrier would cost $175-million and that this was a job which private industry could undertake for much less money. Queried on this point, a top Navy official stoutly denied that any such figures were involved; in fact, he maintained that no cost estimates had been made.

If the Navy Department was miffed by Wilson's decision to cancel CVR, the AEC was sorely dismayed. It was forced to drop $16,350,000 from its budget request for naval reactors. And it had to include a request for $3,700,000 to defray cancellation of the Westinghouse contract for CVR.

Industrial Power Reactor

Caught by surprise, the AEC moved quickly to somehow or other put into its program a reactor for industrial power development. Gordon Dean sent a letter to the White House and put in an appearance before a special meeting of the Joint Congressional Committee on Atomic Energy, of which W. Sterling Cole (R., N. Y.) is chairman.

After Dean's visit to the Joint Committee, Cole sent a strongly worded letter to John Phillips, chairman of the Independent Offices Subcommittee of the House Appropriations Committee. In this letter, dated May 20, Cole stated:

"I believe that it is not only ridiculous but dangerous beyond our ability to foretell that we should not appropriate over a billion dollars for continuing atomic weapon supremacy and yet allow nothing to start building at least one atomic power plant for peacetime use. This is not an act of economy but of folly . . . the argument advanced by Secretary Wilson and Deputy Secretary Kyes in the National Security Council that private companies are ready and willing to put up private capital to do this job is just not true. A mere trickle of private money will be available, and that only when the law (Atomic Energy Act) is changed."

In his letter, Cole urged that the nation undertake to build a prototype of an industrial atomic plant costing $71-million, with costs spread out over a period of from 3 to 5 years. In its appearance before the Appropriations Committee on May 19, AEC asked for $4.2-million to do research and development upon a reactor design similar to that for the abandoned ship reactor—a high-pressure, light-water type, which could power a 250,000 kw-electrical generating plant. The Appropriations Committee approved this, and in addition, $7-million has been made available for the construction of such a reactor.

In commenting upon the program before Congressman Phillips' Appropriation Committee, Gordon Dean stressed the fact that the atomic energy budget contains risks. Aiming his remarks at reactors, Dean said: "I believe, too, that any further reduction in plans for reactor development and research will do a tremendous disservice to the nation. For in this direction most surely lies the greatest promise for the peacetime application of atomic energy over the next decade or more."

Dean's observations, made in 1953, have much the same ring as did David Lilienthal's when he took over as AEC's first chairman. At that time, however, few would have predicted that in 1953 the United States would be without a prototype nuclear power plant. Even the pessimists were not so gloomy. Yet these are the facts. There is no civilian atomic reactor except in the blueprint stage. This is exactly the same condition in which the nation found itself in the first year following the end of the war. We are now told that there is to be an even greater delay in atomic power development because the military crutch upon which the AEC was depending has been weakened by cut-backs in the military program. So, to use the parlance of the day, peacetime atomic power is undergoing a stretch-out.

One can ask "Is it not time to abandon the shaky military crutch and go directly at the task of getting civilian atomic power?" After all, the various industrial study teams which have taken a good hard look at the economic prospects of atomic power have turned in optimistic reports. The technical obstacles in reactor development are no longer considered as prohibitive to building a practical power plant. What then are we waiting for? The one-word answer supplied by the AEC is simply "money."

It is a curious commentary upon our times that we should be lacking money for a sure-thing (an industrial atomic power station) and have plenty for a long-shot (an aircraft propulsion unit). Of course the atomic plane enjoys a military priority. But should not the industrial reactor also enjoy some priority, too? Does industrial atomic power have to continue to be a stepchild to military atomic propulsion?

A clear mandate to promote atomic power development is given to AEC in the Atomic Energy Act. While the Congress is currently inclined to close its purse strings for anything except items of military importance, it is highly doubtful if it would go on record as opposing peacetime development of a new source of power. AEC officials might have to battle it out with the Appropriations Committee, but given a solid program and an aggressive attitude there would be no doubt about the outcome.

—Ralph Lapp

Cole Wants Power Reactor to be Built Soon

Rep. W. Sterling Cole (R., N. Y.), chairman of the Joint Congressional Committee on Atomic Energy, has called for actual construction of a reactor power plant.

In a speech early in June, Cole said, "The time has come to get a full-scale power producing atomic reactor out of the research and development stage, and into the construction stage."

Cole said that if private industry is not ready to do the job with private funds then he believes that the Atomic Energy Commission, with Government money, "should immediately undertake the construction of a prototype, power-producing reactor."

Commenting on the provisions of the Atomic Energy Act, changes in which are now being discussed by his committee, Cole said: "I would regard it as unwise in the extreme if the Atomic Energy Act were to stand in the way of firms who wish to pioneer in this area of enormous technological promise."

On this subject, he also said that his committee had heard no testimony indicating that private industry is ready to build power reactors with its own funds.

AEC Supports New and Enlarged Accelerators

Under the physics program of the research division of the Atomic Energy Commission, 13 accelerators are being built or raised in energy, according to Thomas H. Johnson, director of the division.

The following machines are having their energy increased: the Cornell synchrotron, the Michigan synchrotron, the Cal Tech synchrotron will be raised to 1 Bev, and the Berkeley cyclotron will be raised to 750 Mev.

The following machines are in construction: a 300-Mev synchrotron at Purdue, a 500-kev Cockcroft-Walton at Brown, a 68-Mev proton linac at Minnesota, a 32-inch cyclotron at Oregon, a 10-Mev electron linac at Purdue, an electron pulsed linac for neutron time-of-flight spectroscopy at Yale, the bevatron at Berkeley, and a 1-Bev electron linac at Stanford.

Finally, a 6-Mev Van de Graaff will be ordered by Columbia.

The physics program is being conducted by more than 400 scientists in

with

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The latest count of machines involved in AEC supported studies gives 11 synchrotrons, 7 synchrocyclotrons, 20 cyclotrons, 10 betatrons, 7 linear accelerators, 32 Van de Graaff generators, and 11 research reactors.

Gordon Dean Explains AEC Thinking on Changes in Atomic Energy Act; Sees Need for Work by Industry

The attitude of the Atomic Energy Commission on changes needed in the Atomic Energy Act of 1946 to permit and foster industrial development of nuclear power has been outlined by AEC chairman Gordon Dean. Here is what Dean said in a speech to a meeting of the Edison Electric Institute:

The Commission now feels that the law (McMahon Act) should be modified. The ground rules under which atomic power research is carried on in this country should, in the opinion of the Commission, be changed. There are several reasons why we feel this way.

First, nearly everything that has been done in the nuclear reactor field until now has been done for a government reason. The government has developed reactors to produce plutonium for bombs, to serve as government research tools, and to propel submarines. It also has other projects underway which will lead ultimately to the propulsion of aircraft and large naval surface ships.

Now, however, there is good reason to believe that a demand outside of the government's own sphere of operations is developing for atomic reactors. It is a commercial demand, an economic demand, and a civilian demand. It seems only reasonable to expect that people outside of the government be given a chance to work toward the development of reactors to meet this demand.

Another reason why the Commission feels that the present ground rules should be changed is because the job ahead is a developmental one—a cost-cutting one—the kind of a job that can be done best by skilled people competing with other skilled people who are working toward the same or a similar goal.

Proposed Amendments

As a result, the Commission has, since last September, been giving some very serious thought to what there should be in the way of new ground rules. Our position is that the present federal monopoly should be relaxed to permit wider participation in the power reactor program. To accomplish this we have proposed that the present law be amended to permit:

1. The ownership and operation of nuclear power facilities by groups other than the Commission,

2. The lease or sale of fissionable material under safeguards adequate to assure the national security.

3. The use and transfer of fissionable or by-product materials by the owners of reactors, subject to purchase by the Commission or regulation by the Commission in the interest of health and safety.

The purposes of these changes in the law is to encourage groups outside of the Commission to invest money and talent in the development of economic power reactors. It is obvious, we think, that if we want people other than ourselves to invest money and talent in the development of these power facilities, we must allow them to own or lease the facilities, fuels, and the by-products, subject, naturally, to appropriate controls.

As part of its policy position, the Commission has also proposed that the suggested changes in the law be accompanied by adjustments in the Commission's own practices to permit:

1. As appropriate, the granting of more liberal patent rights in accordance with existing law.

2. A progressively more liberalized information policy in the power reactor field, as justified by need and as permitted by security considerations.

3. The performance in Commission laboratories of such research and development work in the power field as is deemed warranted in the national interest.

Our purpose is to create a temporary environment in which the needed developmental effort can be expected to go forward—a period in which the

Commission is given the power and discretion to encourage the participation of others by granting them certain rights which they now cannot have no matter how much money or how much effort they put into this kind of work.

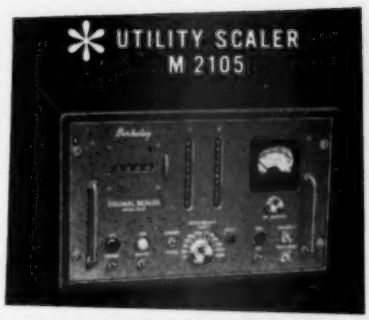
This policy statement by the Commission is an attempt to set up ground rules which are the same for everybody, and when I say everybody I mean federal agencies, state agencies, municipal agencies, and private industry. Everybody who has something to offer to the development of atomic power should be allowed to make a contribution to that development. The idea that some people apparently have that the federal government of this country and the private industries of this country represent two separate and sovereign powers is, in my opinion, most unfortunate. There is only one sovereign power in the country, and that is the federal government. I think it can be relied upon to see that this new force called atomic energy will always be controlled in the public interest, and not, I hope, by monopolistic management but by regulation, and leadership, and the stimulation of competition.

Patents

I think that those who have labeled these proposals as a "giveaway program" have not read them as carefully as they might. Actually, there is only one place where any real rights of the government are at issue in the development of atomic power, and that is in the matter of patents. And yet, if you will look at the Commission's policy statement carefully you will find that it has talked about patents only in the most general terms. In its list of proposed steps, this is what the statement says about patents: "More liberal patent rights than are presently granted to outside groups as may seem appropriate to the Commission and consistent with existing law." You will notice that the statement says, "consistent with existing law." The Commission all along has interpreted the patent provisions of the existing law very rigidly so far as the government's rights are concerned. Present policies can be relaxed to some extent without any change in the law, and therefore without any change in the over-all national policy on the subject of atomic energy patents.

As of now, the Commission has not proposed any change in the patent provisions of the law. This does not mean that it might not do so later.

(Continued on p. 70)



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This question is now under careful study. In this regard, I think there are two objectives:

1. I don't think anyone should be allowed to come into the atomic power picture with the investment of a dollar or two and walk off with patents worth hundreds of millions of dollars.

2. I think people who come into the power program and make a real contribution based on a liberal investment of talent and money involving a real risk, should be entitled to some patent rights denied to others.

During the developmental period we are moving into, I am convinced that industry and government must work together if we are to get the most out of it. During this period, it seems clear to me that some prototypes and pilot plants of atomic power facilities must be built. It is my own opinion that the government, as well as industry, must participate in this kind of endeavor, for, as of today, the investments must be high and the pay-offs a number of years in the future. I would be very pleasantly surprised if private capital were to move in and pick up the total check for this expensive and—at first—unprofitable work.

Why Nuclear Power

I think we want atomic power because as soon as it comes into being it will reduce the rate at which we are using up our other natural resources. It will release them for other uses or permit us to conserve them for future specialized use.

I think we want atomic power because our demand for energy in this country and in the world is increasing at an enormous rate, and the costs of producing such fuels as oil and gas will steadily rise as the supplies dwindle. We will need a supplementary source of energy, and to be ready when the time comes we must push ahead now.

I think also that we need atomic power because atomic fuels are virtually weightless fuels. They can be taken anywhere in the world—to the source of the raw materials upon which industries are based—to deserts, to mountains, and to islands.

I think we need atomic power so that we may help our friends in the world who are in need of new sources of power. I have particularly in mind those who have been and are supplying us with the uranium with which we are feeding our weapons program.

BNL Starts Mail-Order Film-Badge Service

A mail-order nuclear-track film-badge service is now available from Brookhaven National Laboratory under an arrangement with the Atomic Energy Commission's New York Operations Office, health and safety division.

The service was first made available to AEC sponsored research contractors because of the commercial unavailability of such service (as in the case of beta-gamma film badges) and because establishment of a program by each contractor would not be economically feasible. It has now been decided to offer the service to any non-AEC program (in the U. S.) until it becomes available elsewhere.

Anyone interested in taking advantage of the service should communicate with Frederick P. Cowan, Brookhaven National Laboratory, Upton, N. Y.

RAW MATERIALS

• **Australia.** The Rum Jungle uranium field in the Northern Territory is expected to be in full production next year. Plans call for ore production this year, with a treatment plant being erected for full production next year.

• **Idaho.** U. S. production of radioactive monazite sands and their rare earth derivatives suffered a severe setback when a 600-ton bucket-type dredge overturned and sank in its pond near Cascade. The dredge had produced about a third of the nation's monazite.

• **Massachusetts.** A new AEC laboratory at Winchester is in full operation with the primary objective of development and improvement of processes for recovery of uranium from its ores. Operation is by American Cyanamid Co. under contract with AEC's raw materials division.

• **Utah.** A $1.5-million uranium mill is being planned by Vanadium Corp. of American in the vicinity of Hite, on the Colorado River. The mill will serve production in the White Canyon area.

• **Canada.** A new chemical leaching plant has been put into operation to recover uranium from both current and

stockpiled tailings at the Port Radium site of Eldorado Mining and Refining, Ltd.

• **New Zealand.** A project is underway for the use of geothermal steam for the production of heavy water.

IN BRIEF

• **New Mg isotope.** A new isotope of magnesium, Mg^{28}, a beta emitter with a half-life of 21.3 hr, has been produced by the reactions $Si^{30}(\gamma,2p)Mg^{28}$ and $Mg^{26}(\alpha,2p)Mg^{28}$. The half-life is long enough for tracer work and is expected to be valuable in photosynthesis research and animal-metabolism studies.

• **Nuclear power study.** Duquesne Light Co., Pittsburgh, is working on a plan with an independent consulting firm that specializes in nuclear research whereby the two would enter into contract with AEC to study the possibilities of building a power reactor.

• **Dating.** A laboratory for radiocarbon dating has been established at the University of Saskatchewan.

• **Reactor testing station.** Contract awards for construction at the National Reactor Testing Station, Idaho, during 1953 are expected to total around $12-million. The two major construction contracts are for ground testing facilities for a prototype aircraft propulsion reactor and for the construction of an engine test area.

NEWSMAKERS

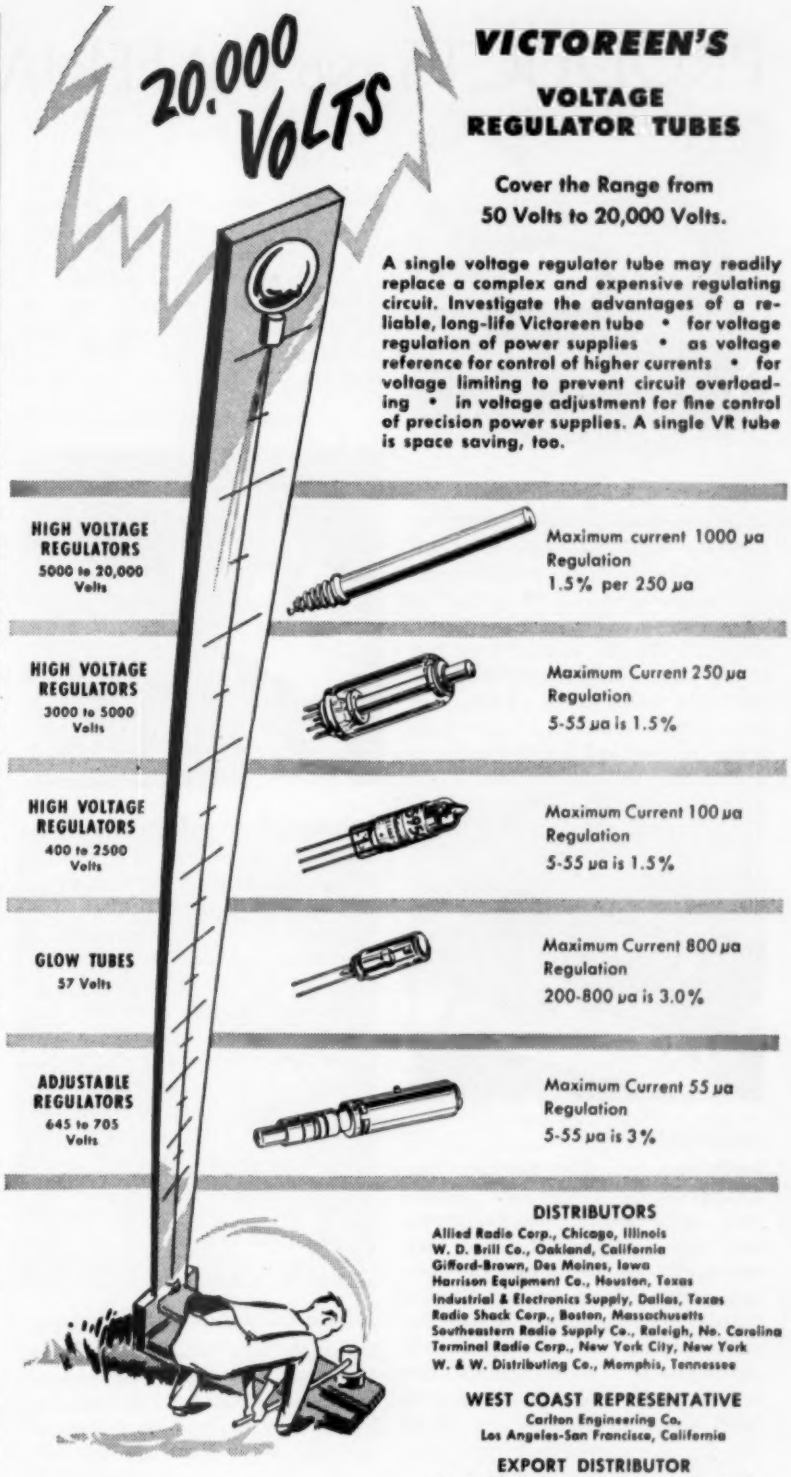
George G. Manov, chief of the advisory field service branch, isotopes division, Oak Ridge National Laboratory, since 1949, is transferring to the AEC office of industrial development, Washington, D. C.

Edward Teller, formerly at the University of Chicago, has been appointed professor of physics at the University of California, Berkeley.

Edgar A. Edelsack, who was head of the radioisotopes unit at the Emery Tumor Group, Los Angeles, has joined the staff of the Naval Radiological Defense Laboratory, San Francisco, as a radiological physicist.

Richard L. Kirk has been appointed director of production of AEC's New York Operations Office.

Joseph A. Thie has joined the reactor engineering division of the Argonne National Laboratory.



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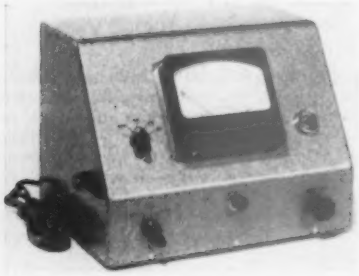
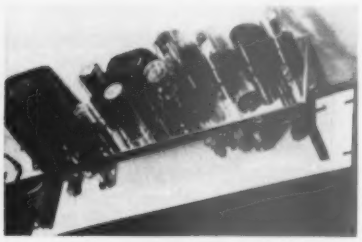


Dosimeter Charger-Reader

Landsverk Electrometer Co., 550 W. Garfield Ave., Glendale 4, Calif. The model L-62 charger-reader accepts four ranges of pocket chambers. A selector switch can be set to the desired range; the chamber reading is not lost if the selector switch is accidentally set to the wrong range. Ranges can be adjusted as desired. Meter scale is marked 0–50 and 0–200; linearity is ±2%. Zero drift is slight and is said to have no effect on readings. (P-1)



Laboratory Monitor

Detectolab, Inc., 6544 Sheridan Rd., Chicago 26, Ill. The Radiation Supervisor continuously monitors a laboratory room. If the radiation level rises appreciably, the instrument automatically indicates it by aural and visual alarms. An infinite-life-type G-M detector is plugged directly into the top of the chassis. Construction includes chrome chassis, baked-on-enamel front panel, and oak cabinet. (P-2)

Stainless-Steel Filters

Micro Metallic Corp., 35 Sea Cliff Ave., Glen Cove, N. Y. Grade X porous stainless-steel filter sheet is available in the form of finished line filters. Tensile strength is 25,000 lb/in. The sheet is said to be more ductile than previously available material. Thicknesses from 0.020 in. to ⅛ in. are available with tolerance of ±0.002 in. This material can be fabricated into all the forms in which porous stainless steel has hitherto been available. (P-3)

Crystal-Growing Furnace

Wakefield Industries, Inc., 5108 W. Grove St., Skokie, Ill. These furnaces, housed in thermostatically controlled ambient-temperature reservoirs, grow organic scintillation crystals from the melt of any desired luminescent material of melting point between 100° and 500° C by the Stockbarger method. Input power to the furnaces is controlled by Variac transformers. Molten phosphor material is transported through a sharp temperature gradient at the rate of 1 in. in 30 hr. Operations are carried out from a control panel. Crystal-cooling facilities are optional equipment. (P-4)

Labeled Compounds

Tracerlab, Inc., 130 High St., Boston 10, Mass. Carbon-14 labeled compounds are available for monomolecular-layer studies, flotation studies, and research in the soap and oil fields. Lauric acid-1-C^{14} and stearic acid-1-C^{14} are available with specific activity of 1.0 mc/millimole; minimum order is 1.0 mc. Added to the amino acids offered is dl-aspartic acid-4-C^{14} with specific activity of 0.5–1.0 mc/millimole; minimum order is 0.1 mc. (P-5)

Pneumatic Ejector Pump

Yeomans Brothers Co., 1999 N. Ruby St., Melrose Park, Ill. The Pneu-Pump pneumatic ejector handles any fluid that will flow into it, including acids, alkalies, molten metals and salts, slurries, and water. It is said to operate at high efficiency even with low volumes. A ball inlet valve is the only moving part. Cast-iron, lead-lined, rubber-lined, or stoneware bodies are available. The pump can be operated from compressed-air supply or, by means of auxiliary equipment, from a steam supply. (P-6)

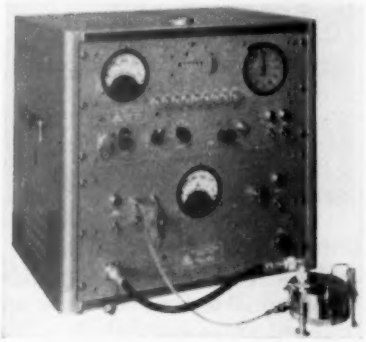
Electronic Counter

Hewlett-Packard Co., 395 Page Mill Rd., Palo Alto, Calif. The model 522B direct-reading counter measures rate of occurrences from 0.00001 to 100,000 per sec, time from 10 μsec to 27.8 hr, and periods of 1/1,000, 1/100, 1/10, 1 and 10 sec or multiples. Measurements can be made without additional equipment or with standard transducers. (P-7)

Automatic Sample Changer

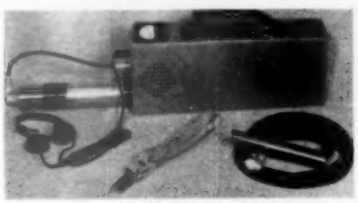
Nuclear Instrument and Chemical Corp., 229 W. Erie St., Chicago 10, Ill. The model C-110 sample changer carries up to 50 radiolabeled samples. A three-position turntable selects a

sample, places it in counting position within the 2-in. lead shield, and loads it into the storage sample magazine after the count is recorded. The unit has eight preset-count settings; it may also be controlled by a preset-time or -count scaler. The associated timing printer provides a permanent count record. (P-8)



Counting System

Radiation Counter Laboratories, Inc., 5122 W. Grove St., Skokie, Ill. The mark 9 model 4 Nucleometer is a complete counting system for alpha, beta, or gamma radiations. It consists of a preflush flow counter, high-voltage supply, pulse amplifier, pulse equalizer, scaling circuit, register, and timer. Amplifier-section characteristics: input sensitivity, 3–50 mv; gain, 1,000; amplifier rise time, <0.5 μsec, and decay time, <3.5 μsec; output, 0–10 volts, negative; resolving time, <5 μsec; high voltage, 2,300–5,000 volts, continuous; and output-voltage regulation, $<0.01\%$ for 1% line-voltage change. Scaler-section characteristics: input capacity, 100 $\mu\mu$f; input sensitivity, 0.25–5 volts, negative; voltage range, 500–2,000 volts, $\pm 2\%$ of full scale; resolving time, 5 μsec; scaling factors, 64, 128, 256, or 512. (P-9)



G-M Survey Counter

The Radiac Co., Inc., 489 Fifth Ave., New York 17, N. Y. The model 105-D survey instrument can be used for prospecting on foot or from low-flying aircraft or a moving vehicle, or for probing drill holes to depths of 50 ft. Overall length of the G-M tube is 26 in. and diameter is 2 in.; it can be taken out of the instrument and fitted to the 50-ft coaxial cable provided. The tube is claimed to have a sensitivity 30 times greater than that of a standard-size G-M tube. A standard-size β-γ G-M probe is interchangeable with the large-size tube. (P-10)

Corrosion-Resistant Tanks

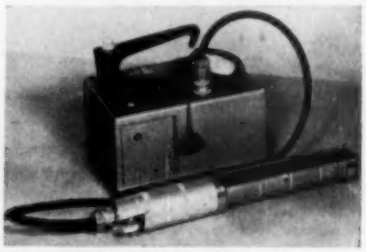
American Agile Corp., Box 168, Bedford, Ohio. These corrosion-resistant tanks are fabricated throughout of unplasticized polyvinyl chloride. Mainly of welded construction and entirely selfsupporting, they are built to customer's specifications. The tanks are resistant to most mineral acids, alkalis, inorganic salts, and many organic compounds at temperatures up to 170° F. Tanks are furnished with inlets, outlets, and standard flanged fittings. (P-11)

Frequency Meter

Beckman Instruments, Inc., Berkeley Scientific Div., 2200 Wright Ave., Richmond, Calif. The model 5570 frequency meter is a direct-reading instrument for measuring zero cps to 42 Mc. Accuracy is ± 1 count, $\pm$ crystal accuracy. Input requirement is 1 volt, rms, with 50-ohm impedance. Display time is 1–5 sec, continuously variable; time base is 0.00002, 0.0002, 0.002, 0.02, 0.2, and 2 sec. Accessories extend range to 160 Mc. (P-12)

Scintillation Counter

Nuclear Research Corp., 2563 Grays Ferry Ave., Philadelphia 46, Pa. The SC-2A scintillation counter has a gamma-detection efficiency $>35\%$ for Co^{60}, $>75{,}000$ cpm/mr/hr for Ra, and $>50\%$ for I^{131} (2,200 cpm over background per μc at 15 cm). A magnetically shielded RCA 6199 photomultiplier tube is permanently sealed to a 1×1 in. NaI(Tl) crystal. Starting potential is $1{,}000 \pm 100$ volts; operating potential is $1{,}100 \pm 100$ volts. Plateau slope is $<10\%/100$ volts with no shield and $<5\%/100$ volts with lead shield; plateau length is >150 volts. (P-13)



Survey Meter

Radioactive Products, Inc., 443 W. Congress St., Detroit 26, Mich. The model D-5 survey meter is said to provide greater stability and versatility than the original model. With models D-5A and D-5B probes, it covers radiation ranges from low-level alpha contamination to 625-mr/hr gamma radiation. Large flat areas, irregular surfaces, or holes and corners can be monitored. The instrument includes a plug-in battery box, a roll-over-bottom stainless-steel screen to minimize contamination traps, and a neon flashing light to indicate when it is in operation. (P-14)

Humidity Control

Niagara Blower Co., 405 Lexington Ave., New York 17, N. Y. Without the need for a moisture-sensitive element, this air conditioner dehumidifies air

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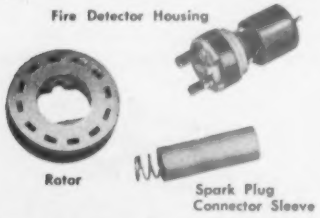

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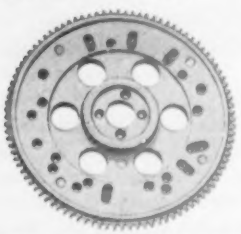

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directly by a liquid absorbent. As the air conditioner removes moisture from the air stream passing through it, the absorbent liquid becomes diluted and is continuously reconcentrated to keep it effective. A thermostat, which measures the boiling point of the water-absorbent mixture, operates the concentrator unit to furnish a greater or less concentration of the absorbent liquid. Since a change of several degrees in the boiling point of the absorbent liquid is required to effect a change of 1% in its concentration, the control is claimed to be extremely accurate. (P-15)

Regulated Power Supply

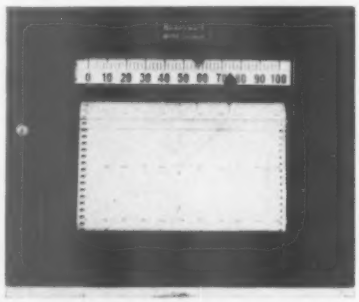
Kepco Laboratories, Inc., 131–38 Sanford Ave., Flushing 55, N. Y. The model 750 power supply was incorrectly illustrated in the May issue (p. 78). This supply is continuously variable from zero to 600 volts and delivers 0–750 ma, d-c. (P-16)

Voltage Stabilizers

Raytheon Mfg. Co., Equipment Sales Div., Waltham 54, Mass. This new line of voltage stabilizers can stabilize any fixed load to ½% for any line change and to 1% for frequency change. The first model operates on an input of 115 volts ±10%, 58–62 cycles, single phase, and provides an output of 115 volts, 2,000 volt-amperes. Third harmonics at 60-cycle input show less than 5% total. (P-17)

Selenium Regulators

International Rectifier Corp., 1521 E. Grand Ave., El Segundo, Calif. The type D-568 selenium regulator is designed for d-c voltages in the order of 1.5 volts. The regulator is connected in shunt with the load; a voltage-dropping resistor is connected in series with the source voltage and load. Regulation is accomplished by utilizing the forward characteristic. Voltage across the voltage-dropping resistor varies inversely with changing load current. (P-18)



Differential Recorder

Minneapolis-Honeywell Regulator Co., Industrial Div., Wayne and Windrim Aves., Philadelphia 44, Pa. The Duplex Electronik strip-chart recorder is adaptable for differential temperature and BTU recording on the same chart in a nuclear reactor power calculator system. A system to measure reactor power, such as one developed by Minneapolis-Honeywell, would include, besides temperature and BTU recorders, a flow meter. (P-19)

High-Voltage Power Supply

Scientific Specialties Corp., Snow & Union Sts., Boston 35, Mass. The model PS-71 d-c power supply provides 1,000–5,000 volt output rated for 1-ma load. Output voltage changes <0.05% from zero to full load. A 10% change in input voltage causes <0.05% change in output. Ripple is <0.03% of output. (P-20)

Electronic Wattmeter

Keithley Instruments, 3868 Carnegie Ave., Cleveland 15, Ohio. The model

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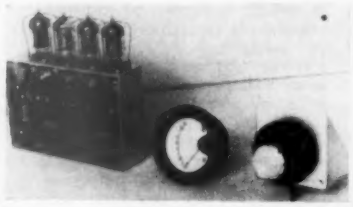
110 wattmeter, basically an amplifier driving the potential coil of a dynamometer wattmeter, has a range of 0.3–300 watts on 6 scales with accessory shunts extending the range to 9,000 watts. Accuracy is within 2% of full scale. Frequency response is 20–3,000 cps; input impedance, 500,000 ohms to the potential circuit, 0.5 ohm to current circuit. (P-21)



Decade Counting Assembly

Digital Instrument Co., Inc., Box 1246, Coral Gables, Fla. The model 100 digital decade-counting assembly was incorrectly illustrated in the April issue (p. 82). This assembly may be used as a simple divider, a counter with indicator, or as a preset counter with indicator. (P-22)

Circuit Tracer

Delta Electrical Specialty Co., 1456 E. Walnut St., Pasadena, Calif. The Desco Circuitracer traces circuits for continuity and presence of either d-c or a-c voltage. Live circuits of 2–600 volts, dead circuits, and devices can be tested; it can be used as a high- or low-voltage tester for live circuits. Trace indication is by means of a signal light at point of contact. (P-23)

Signal Generator

Wang Laboratories, 296 Columbus Ave., Boston 16, Mass. The model DS-157 signal generator, operating on the dot sequential principle, provides characters at 10,000 per sec for display on a cathode ray tube. Format is 5 horizontal × 7 vertical dots. Unit has

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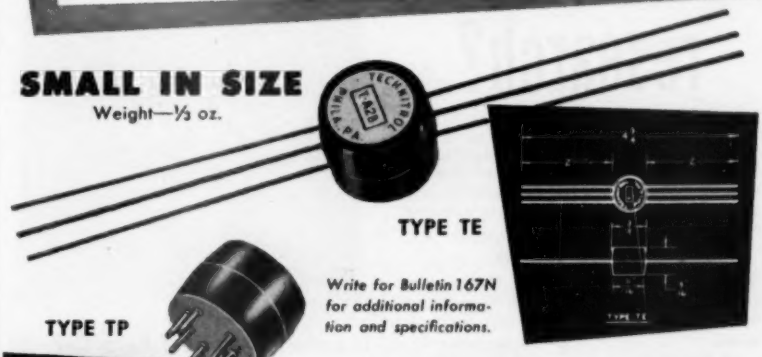

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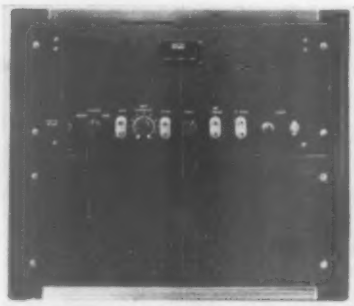
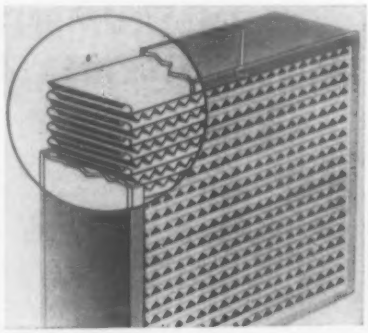


Magnetic Transient Recorder

Magne-Pulse Corp., 140 Nassau St., New York 38, N. Y. The type 103 magnetic transient recorder permits oscilloscope recording and display of one-shot or irregular frequency phenomena containing components from d-c to 30 kc. The recorder makes possible the reproduction of square waveforms with the use of pulse-time modulation. (P-25)



Filter Units

Mine Safety Appliances Co., Braddock, Thomas and Meade Sts., Pittsburgh, Pa. These filter units, using a matted paper made of asbestos and cellulose fibers, remove particles as fine as 0.05 micron from the air. Resistance of the filter unit at a flow velocity of 5 ft/min is 1 in. of water at 65–75° F. Four filter sizes have capacities up to 1,000 ft³/min. The largest size provides 300 ft² of filter media in a unit $24 \times 24 \times 11\frac{1}{2}$ in. over-all. (P-26)

Vibration Pickup

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Potentiometers

Birklan Corporation, 200 E. Third St., Mount Vernon, N. Y. The series 3500 potentiometers, in the resistance range 2,000–300,000 ohms, have a linearity of 0.01%. Resistance values down to 500 ohms are available with linearity of 0.02%. Temperature range of operation is 0–80° C. Resolution is up to 0.0024%. Electrical and mechanical rotation may be specified from 360 to 3,780 ± ½ deg. A built-in traveling nut-type limit stop is sufficiently rugged to serve as the mechanical limit stop in most instrument servos. (P-28)

Wide-Range A-C Ammeter

Millivac Instrument Corp., 444 Second St., Schenectady 6, N. Y. The type MV-121 shunt box, when used with the type MV-12A voltmeter, provides an a-c ammeter covering the following ranges: 1-μa to 3-ma range, 20 cps to 250 kc; 1-ampere range, 20 cps to 100 kc; 3-ampere range, 20 cps to 6 kc. Frequency response is within 0.2 db. Wave shapes may be observed by plugging oscilloscope into the output terminal of the voltmeter. (P-29)

Densitometer

W. M. Welch Scientific Co., 1515 Sedgwick St., Chicago 10, Ill. The Densichron densitometer, used for quantitative paper-chromotography analysis of amino acids, has errors of 17% or less for single determinations;

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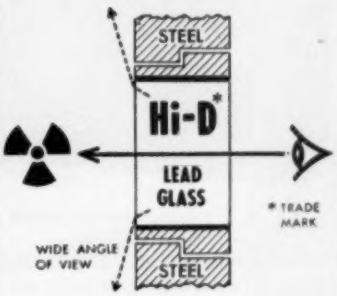

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INDUSTRY NOTES

▶**Radiation Instrument Development Laboratory,** 2337 W. 67th St., Chicago, Ill., has set up a division for reactor control equipment, custom built in accordance with ORNL practice. Instruments are directly interchangeable with equipment now in use at Oak Ridge and other national laboratories.

▶**Minneapolis-Honeywell Regulator Co.,** Wayne & Windrim Aves., Philadelphia 44, Pa., is opening a new plant at Warren, Ill., to expand production of the Micro Division.

▶**Allen B. Du Mont Laboratories, Inc., Instrument Div.,** has devoted its new 118,000-sq.-ft plant, at 760 Bloomfield Ave., Clifton, N. J. to manufacture of cathode-ray-tube instruments. It is claimed to be the world's largest plant manufacturing these instruments.

▶**Walter Kidde Nuclear Laboratories, Inc.,** 975 Stewart Ave., Garden City, N. Y., has appointed G. B. Webb as a senior process engineer. Mr. Webb's previous work has included design and engineering of the Oak Ridge gaseous diffusion plant for the Kellex Corp. and design of a deuterium-separation plant for Hydrocarbon Research, Inc.

LITERATURE AVAILABLE

Electronic equipment. Catalog 5302 describes line of oscilloscopes, amplifiers, pulse generators. *Tektronix, Inc., Box 831, Portland 7, Ore.* (L-1)

Radiation detection equipment. Bulletin presents technical specifications on counters, linear amplifiers, scalers, and radiation safety devices. *Radiation Counter Laboratories, Inc., 5122 W. Grove St., Skokie, Ill.* (L-2)

X-ray analysis chart. Chart, 22½ × 29 in., shows analysis curve for an illium alloy. *North American Philips Co., Inc., Research & Control Instru-*

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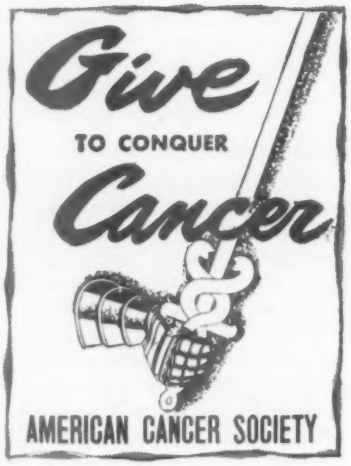

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ments Div., 750 S. Fulton Ave., Mount Vernon, N. Y. (L-3)

Instrumentation case histories. "Instrumentation" index covers 300 technical case histories plus other information. *Minneapolis-Honeywell Regulator Co., Industrial Div., Wayne & Windrim Aves., Philadelphia 44, Pa.* (L-4)

Civil defense instruments. Bulletin C-3 describes equipment for radiation monitoring. *Landsverk Electrometer Co., 550 W. Garfield Ave., Glendale 4, Calif.* (L-5)

Instrument motors and accessories. Catalog describes line of miniaturized hysteresis, synchronous, control, and damped-control instrument motors. *Servomechanisms, Inc., Post & Stewart Aves., Westbury, N. Y.* (L-6)

Kel-F polymers. Bulletin 1-3-53 gives properties and applications of polymers. *M. W. Kellogg Co., Chemical Mfg. Div., Technical Service Dept., Box 469, Jersey City 3, N. J.* (L-7)

Automatic moisture tester. Folder describes Aquameter, an electronic device for automatic moisture titration. *Beckman Instruments, Inc., S. Pasadena 1, Calif.* (L-8)

Spot film radiography. "Spot Film Radiography," by S. M. Wyman, M. D., describes method in detail. *Frank Scholz X-Ray Corp., 112 Cummington St., Boston, Mass.* (L-9)

Centrifugal pumps. Bulletin 08B61-46B describes single-stage, double-suction centrifugal pumps. *Allis-Chalmers Mfg. Co., 1316 S. 70th St., Milwaukee, Wis.* (L-10)

Liquid-level gages. Data sheets cover line of valves for tubular and flat gages, regular, offset, and with union connections to gage. *Jerguson Gage & Valve Co., 80 Fellsway, Somerville 45, Mass.* (L-11)

Compressed-air purifier. Bulletin describes unit for producing instrument-quality compressed air from ordinary plant air. *Hankison Corp., Biltmore Building, Pittsburgh, Pa.* (L-12)

Control relay. Booklet B-5817 gives application and design information on type N remote-control relay. *Westinghouse Electric Corp., Box 2099, Pittsburgh 30, Pa.* (L-13)

Laboratory furniture. Catalog 4B illustrates line of laboratory furniture and equipment. *Metalab Equipment Corp., Hicksville, N. Y.* (L-14)

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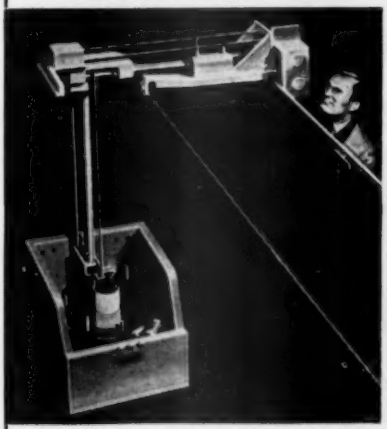

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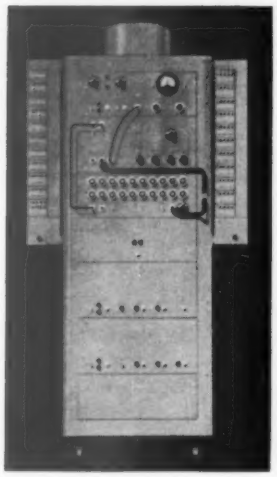

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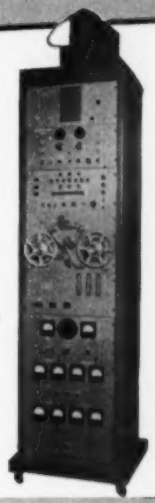
Model 520 Twenty Channel Differential Pulse Height Analyzer — for pulse amplitude distribution studies, divides a spectrum of 60 volts at input of Pulse Sorter into 120 channels, scanning 20 at a time. May be used to study any phenomena where events are expressed in terms of electrical pulses with random amplitudes. Each channel output is fed to a scale of 16 and register for visual indication. All scalers and registers reset by single push button.

Model 510 Single Channel Differential Pulse Height Analyzer for study of amplitude distribution of pulses in the range from zero to 100 volts.

DATA PRINTER

Model 10ABC Analog Voltage Scaler and Rapid Numerical Printer — for reduction of electrical data to printed numerical form. Data in the form of an analog voltage (a direct voltage, the magnitude of which is directly proportional to the represented data value), or in one of several digital forms, may be printed in three-digit Arabic numerals at a rate of 10 to 600 values per second. Figures are printed virtually instantaneously by an all-electronic system on paper tape and no processing is required. When data is in analog form, overall scaling accuracy is ± 0.4%, while digital data is printed with no error.



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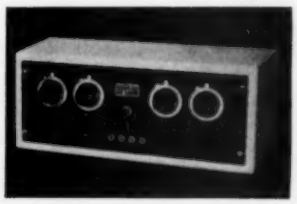
Model 1070A Multiscaler (shown) — a complete scaler for all types of nuclear research; Geiger, Scintillation, or Proportional techniques. Fully automatic operation, with optional choice of five microsecond or one microsecond resolution. Available as decade, scale of 1000 or binary, scale of 4096; also includes built-in pulse amplifier.

Several other models in this Ten-Ten Series are available, each with choice of many features to "customize" scaler for your needs.

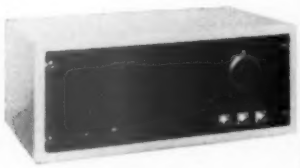
COINCIDENCE ANALYZERS



Model 502 Four Channel Coincidence Analyzer — specifically designed for operation with Geiger Counters in cosmic ray or nuclear physics research and for general radioactivity experiments. Any combination of the four channels can be used in coincidence and one channel can be put into anticoincidence. Resolution of 0.25, 0.5, 1 or 2 microseconds selectable for each channel.

Also Model 503C Two Channel Anticoincidence Analyzer — for low level GM tube measurement. Other models available.

LINEAR AMPLIFIERS



Model 204C Linear Amplifier — for use with ionization chambers, scintillation and proportional counters. This model has separate input time constant and rise time settings; gain control by coarse attenuator. Several other models of amplifiers and preamplifiers available.

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Model 410 Count Rate Meter — for general laboratory use. Four selectable ranges: 0 - 200 - 2,000 - 20,000 - 200,000 CPM with 2% accuracy. Direct, scintillation and GM probe inputs. High voltage supply, 400 to 2000 V @ 1 ma; 0.05 percent regulation. Includes aural monitor and output for standard 1 ma. pen recorder.

Also Model 409 Laboratory Monitor — a compact bench monitor, with 5% accuracy, for routine laboratory contamination monitoring and many other applications. Various model probes available.

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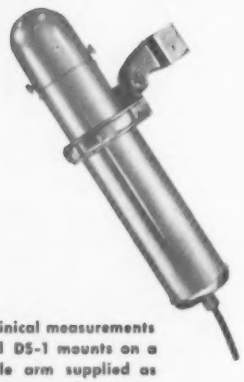
BECAUSE scintillation counters offer the most efficient means of gamma counting, Nuclear-Chicago has developed specialized units for specific gamma determination methods. Models are available for laboratory or clinical counting with high efficiency.



For clinical measurements Model DS-1 mounts on a flexible arm supplied as part of a complete counting unit.

- Samples with activities of .0001 microcurie or greater. Choose Model DS-1 with Model 3036 for least cost and greatest versatility.
- Samples with activities as low as .00001 microcurie. Choose Model DS-3, complete with well type scintillation crystal and shielding, for accurate measurement and maximum geometry. For sample volumes less than 2 ml, the instrument is insensitive to sample volume.
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